Higgs Results from CMS

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On behalf of the CMS Collaboration

Higgs and Beyond the Standard Model Physics at the LHC
The Abdus Salam International Centre for Theoretical Physics
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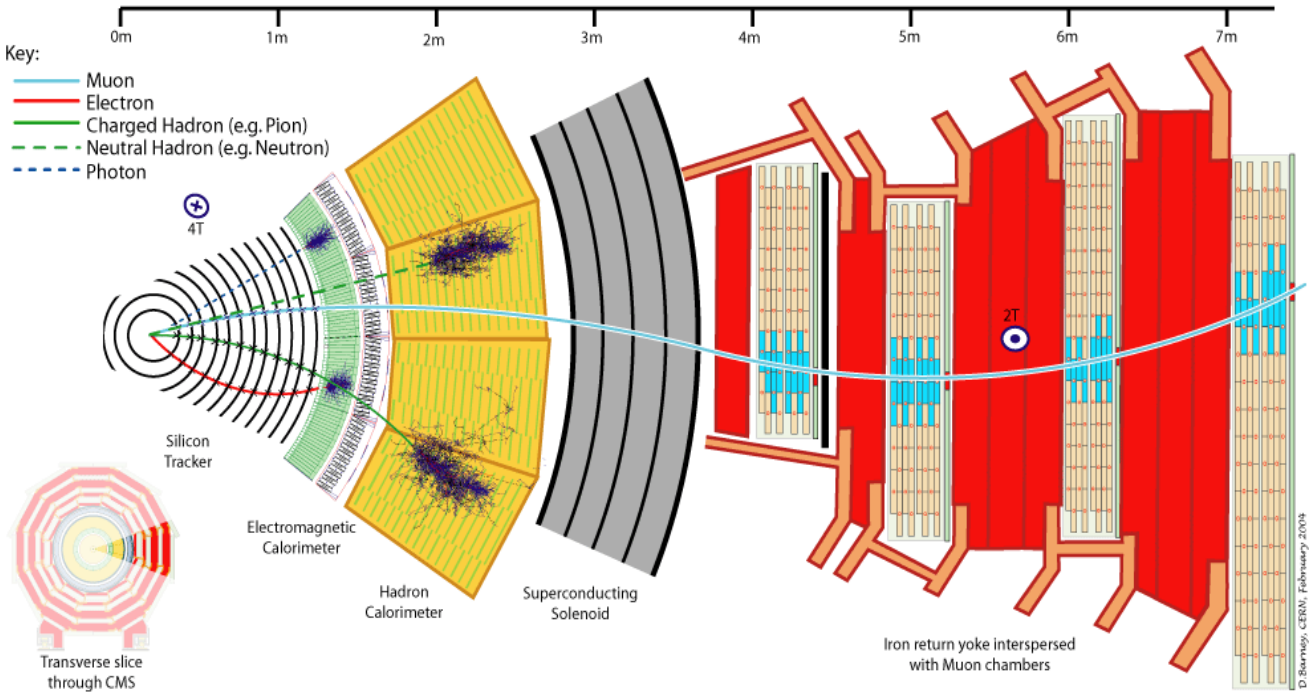
Outline

- Introduction
- SM Higgs Studies
  - Analysis in the bosonic decay channels at low mass
  - Analysis in the fermionic decay channels
  - Measurement of the H125 Higgs boson properties
- Other Higgs Searches
  - High mass Higgs boson searches
  - Fermiophobic Higgs
  - Extended Higgs models
- Summary

For all CMS public results on Higgs searches see:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

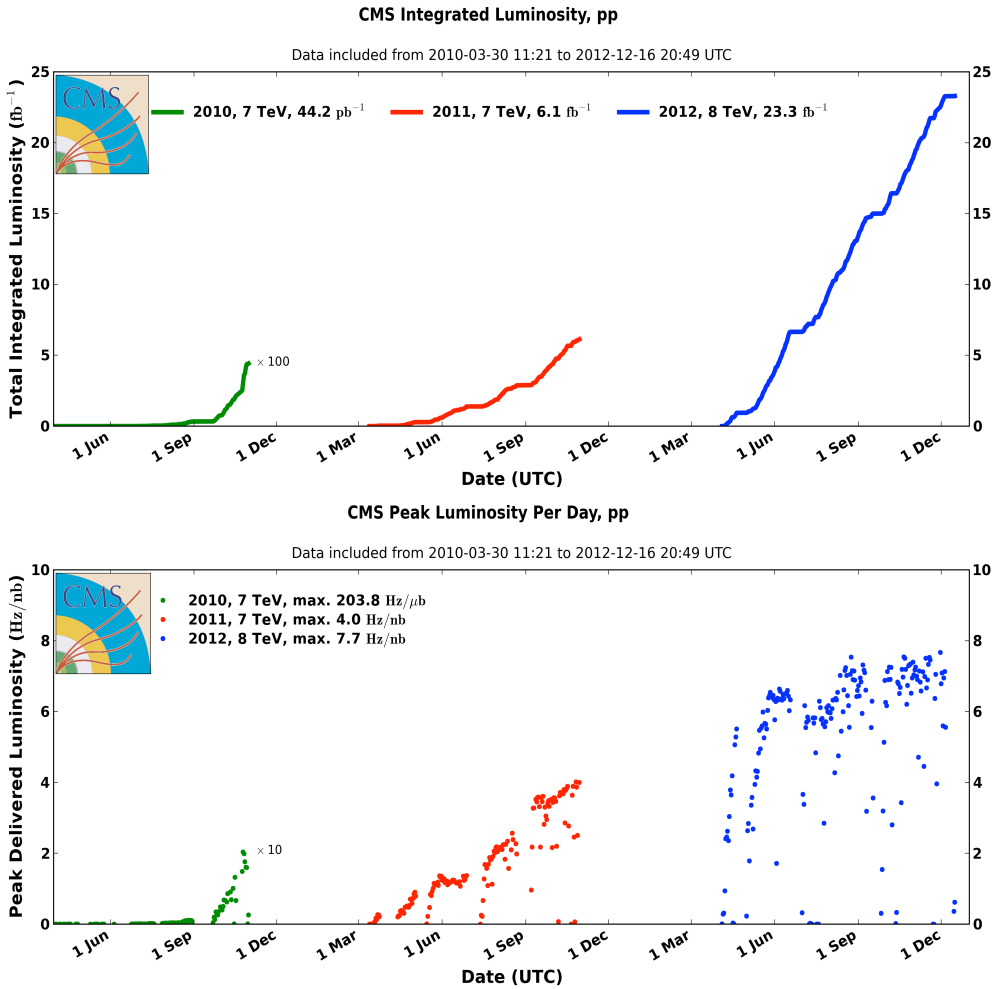
Measurement of particles in CMS



- Global Event Description (GED) - particle flow algorithm
  - combines and links signals from the different sub-detectors
  - provides the optimal event description in form of a list of particles: electron, muons, charged hadrons, photons and neutral hadrons
- τ lepton, jet and MET reconstruction are based on GED
- Large improvements obtained w.r.t. simple reconstruction
- Helps a lot in high PU environment

Data: pp collision at 7 and 8 TeV

- Excellent performance of LHC and CMS in 2011 and 2012
- 25 fb^{-1} IntL pp collisions collected until now at 7 and 8 TeV CM energy

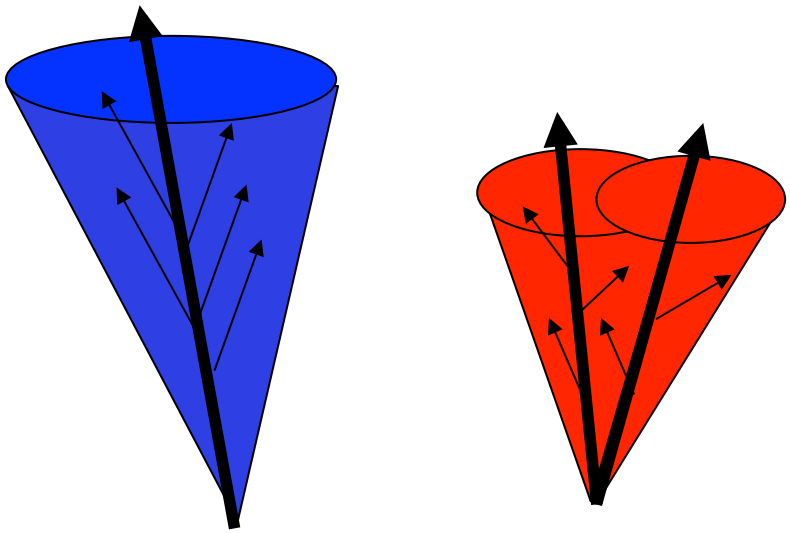


Peak luminosity 7.7×10^{33} $cm^{-2}s^{-1}$

Data taking efficiency >90%

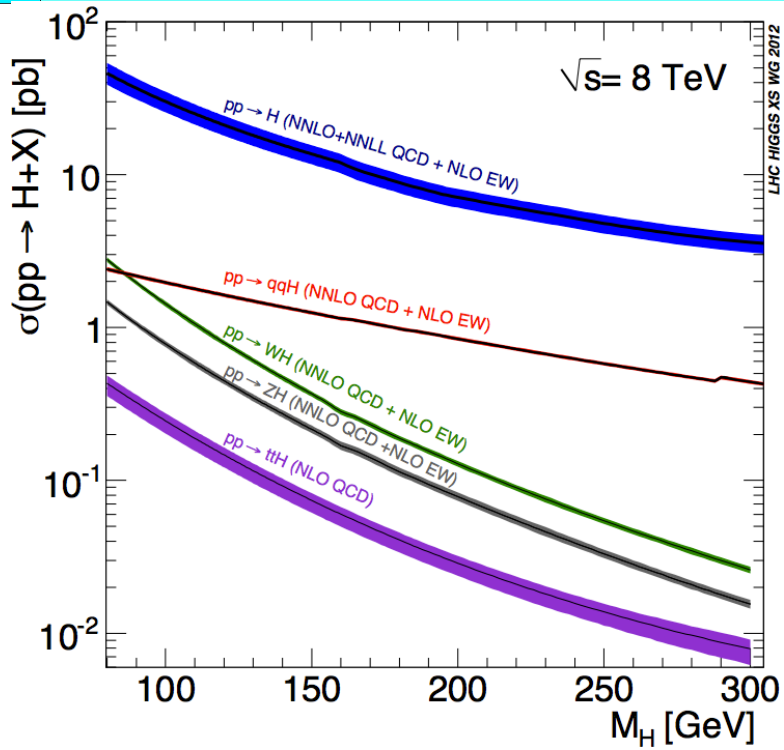
Pileup

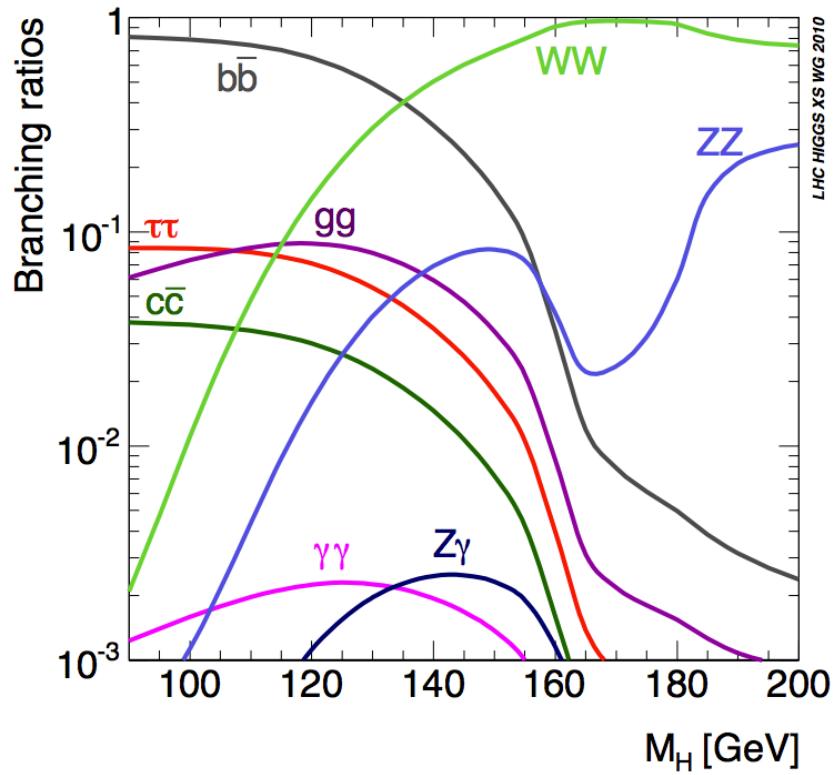
- Multiple interactions occur for each bunch crossing (in-time and out-of-time pileup)
- Mean PU ~10 events in 2011 and ~20 events in 2012
- Effects of pileup:
  - Slightly deteriorates energy resolution for electrons and photons and jets
    - Apply corrections event by event for photons and jets
  - Adds energy in isolation cones
    - corrected for pileup energy estimated event by event
  - PU jets affect central jet veto and VBF jet tagging
    - Try to reject PU jets (wider and with tracks coming from different PV)



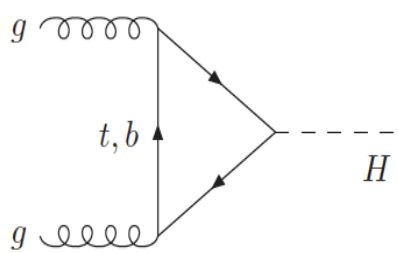
Typical jet Typical Pileup jet

SM Higgs production and decay

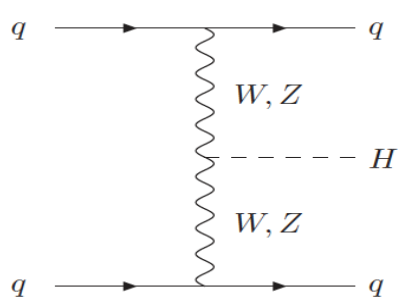




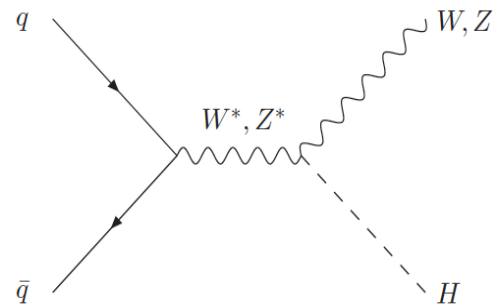
ggH



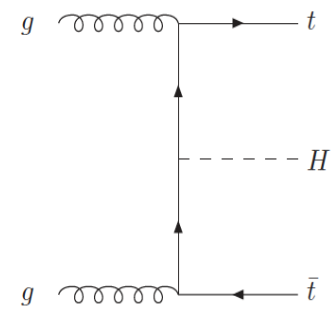
VBF



VH



ttH



Exploit all four production modes

Most sensitive search channels at 125 GeV

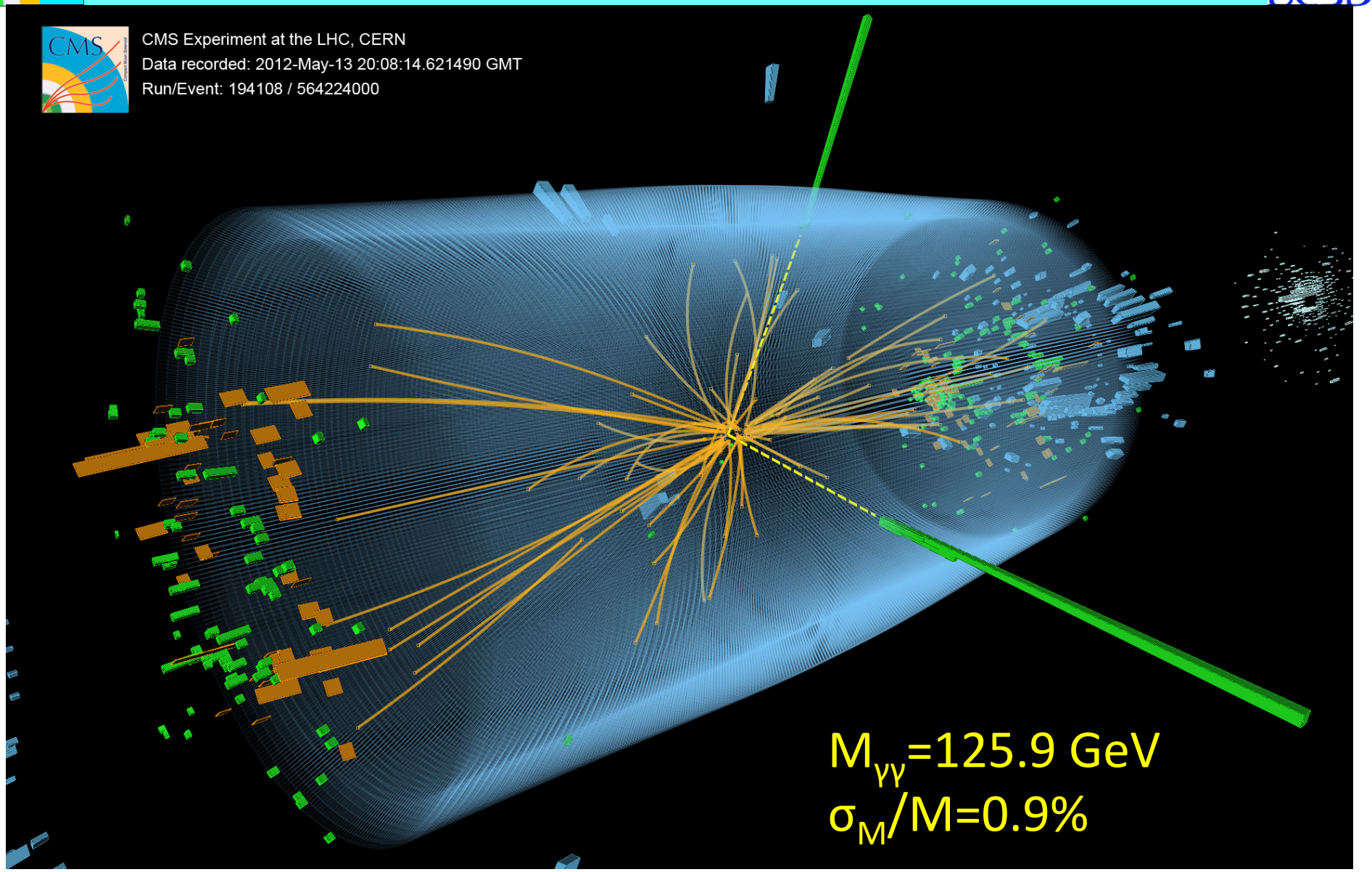
- 2 channels with excellent mass resolution (1-2%)
  - γγ and ZZ -> 4l
  - Search for mass peak over the BG (large BG for γγ and small for ZZ)
- 3 channels with worse mass resolution (10-20%)
  - WW -> 2l2ν, ττ and bb
  - Search for excess above estimated BG
- Zγ has good mass resolution but less sensitivity

Channel	Int Luminosity 7 + 8 TeV (fb^{-1})	Mass resolution	Expected sensitivity	Observed error on σ/σ_{SM}
γγ	5.1 + 19.6	1%	4.2 σ	0.27
ZZ->4l	5.1 + 19.6	1.5%	6.9 σ	0.26
WW->2l2ν	4.9 + 19.5	20%	5.1 σ	0.21
ττ	4.9 + 19.6	15%	2.6 σ	0.4
bb(VH)	5.0 + 19.0	10%	2.1 σ	0.5

Bosonic decay channels

- $H \rightarrow \gamma\gamma$
- $H \rightarrow ZZ$
- $H \rightarrow WW$
- $H \rightarrow Z\gamma$

H→γγ

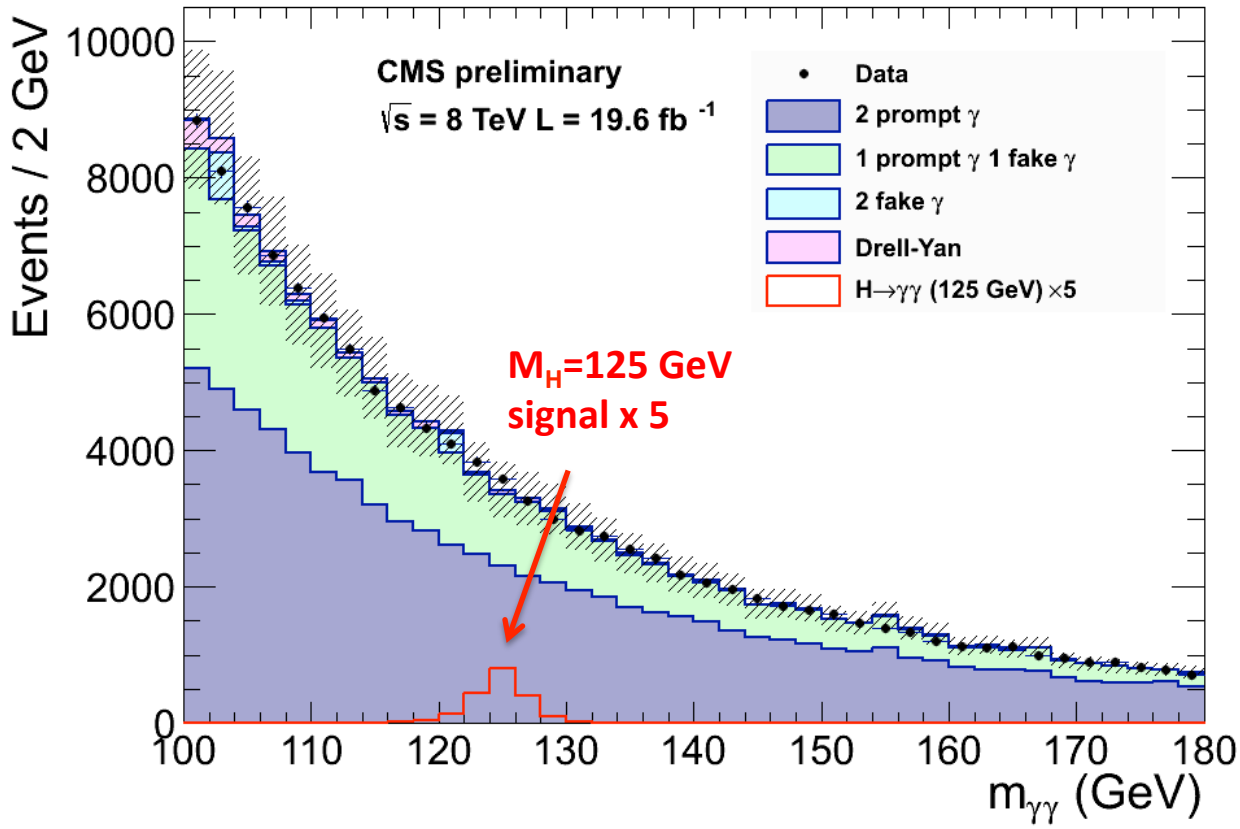

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
$M_{\gamma\gamma}$=125.9 GeV
σ_M/M=0.9%

H→γγ analysis strategy

- Search for a small mass peak over large and smooth background
  - Irreducible: 2γ QCD production
  - Reducible: γ+jet with 1 additional fake photon, QCD with 2 fake photons, DY with electrons faking photons

MC BG not used for deriving results, only for selection optimization

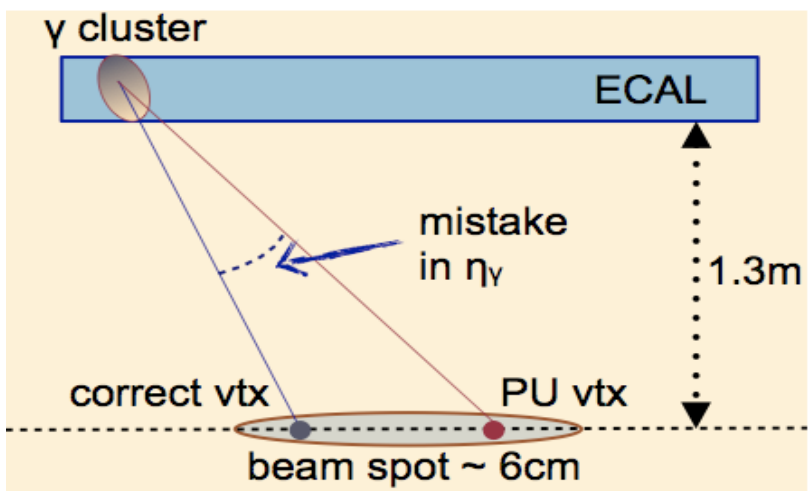
Small BR: ~2×10^{-3}
Two isolated high E_t photons



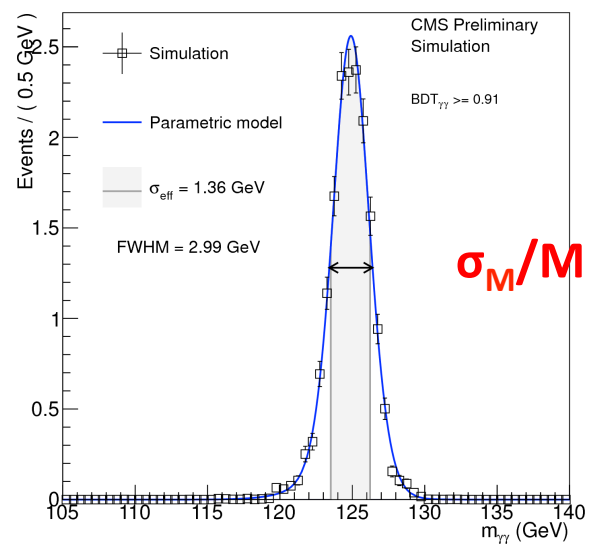
- **Narrow mass peak**
  - resolution 1-2%
- Studied mass range: 110-150 GeV

Ingredients of the Analysis

- **Photon Selection**
  - MVA, based on isolation, shower shape and electron rejection
  - Also cut-based optimized in different categories with different BG levels
    - Barrel/endcap
    - Converted/unconverted identified with shower shape in ECAL
- **Primary Vertex Identification**
  - Primary Vertex is identified using tracks from recoiling jets and underlying event + conversion
  - Found correct in ~80% of cases for pileup in analyzed sample



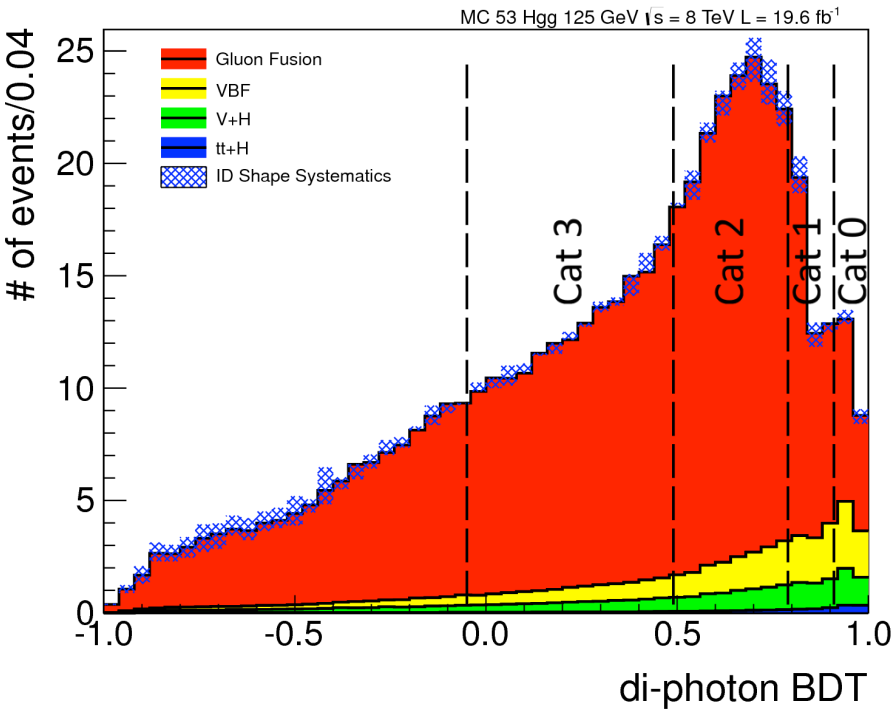
- **Mass resolution**
  - Most important aspect of analysis
  - ECAL response calibrated with $\pi^0 \rightarrow \gamma\gamma$, $W \rightarrow e\nu$ (E/p), $Z \rightarrow ee$
  - Laser corrections measuring transparency loss are applied

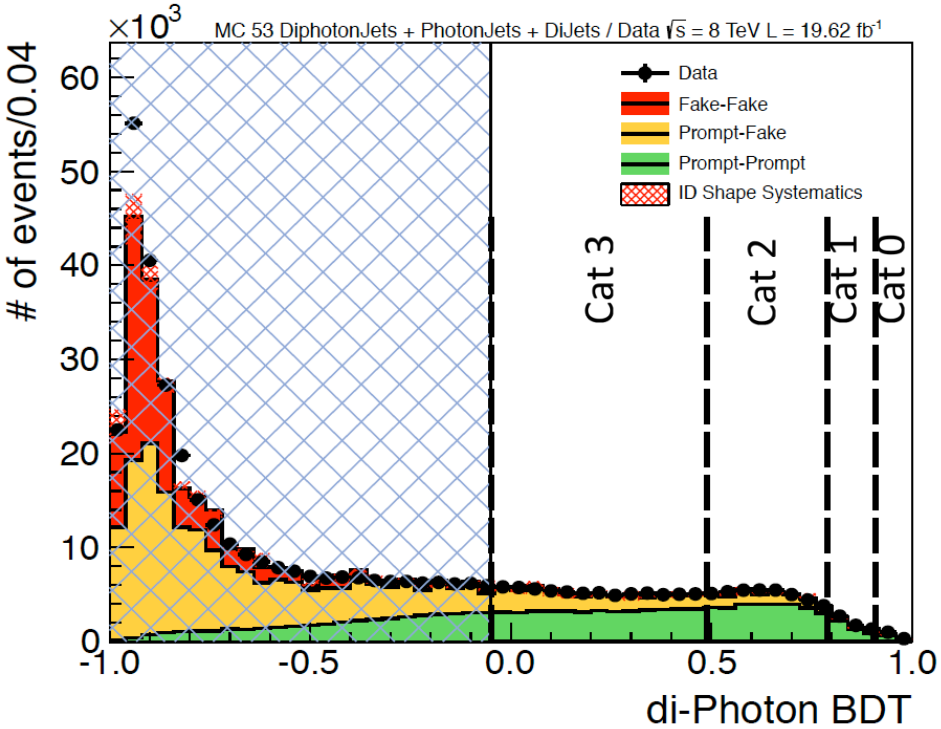


$\sigma_M/M \sim 1\%$

H→γγ analysis

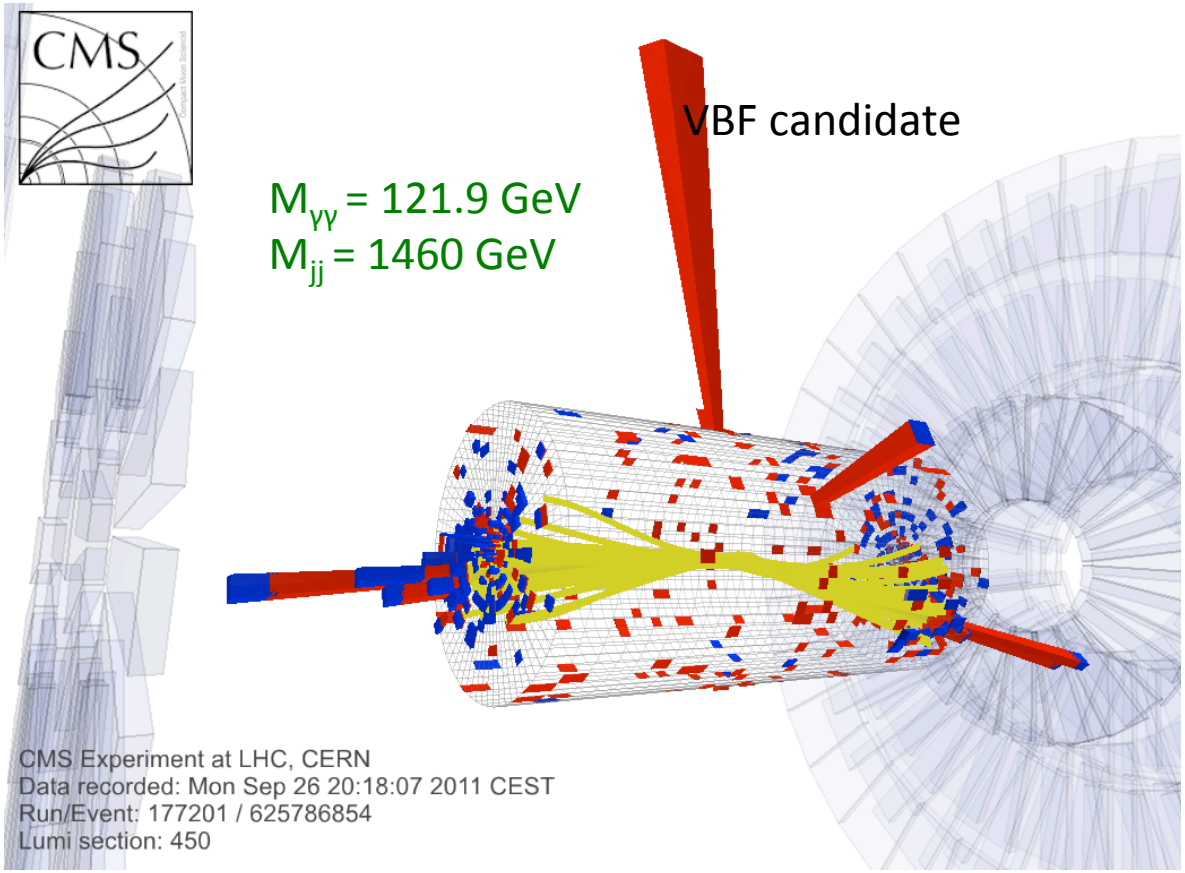
- 4 event classes based on a diphoton Boosted Decision Tree (BDT) output
- BDT inputs:
  - Kinematic information, photon Id classifier, estimated mass resolution
- Additional exclusive classes for VBF and VH





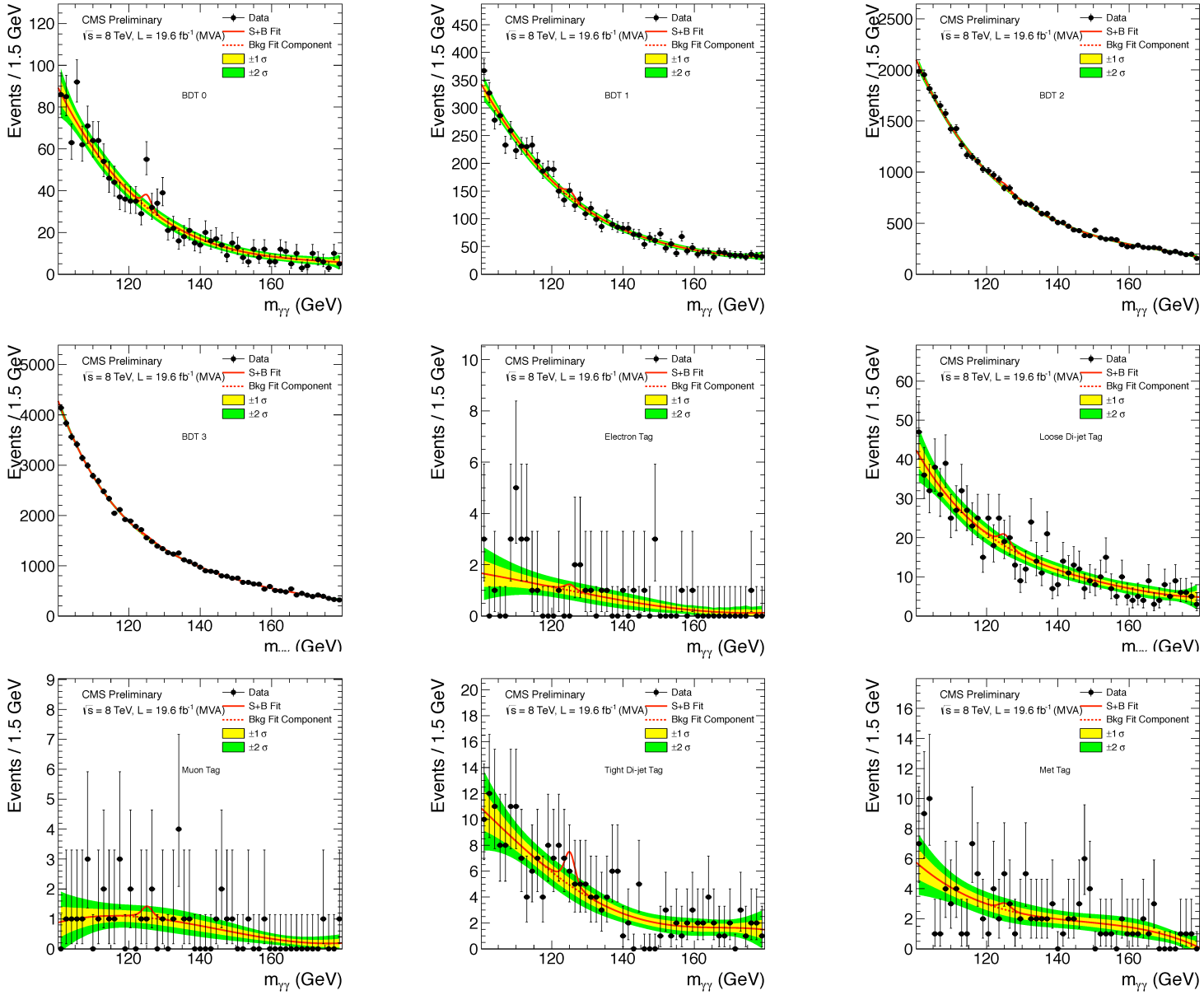
H→γγ exclusive channels

- Add exclusive categories to address specific production processes:
  - VBF -> dijet selection (dijet BDT)



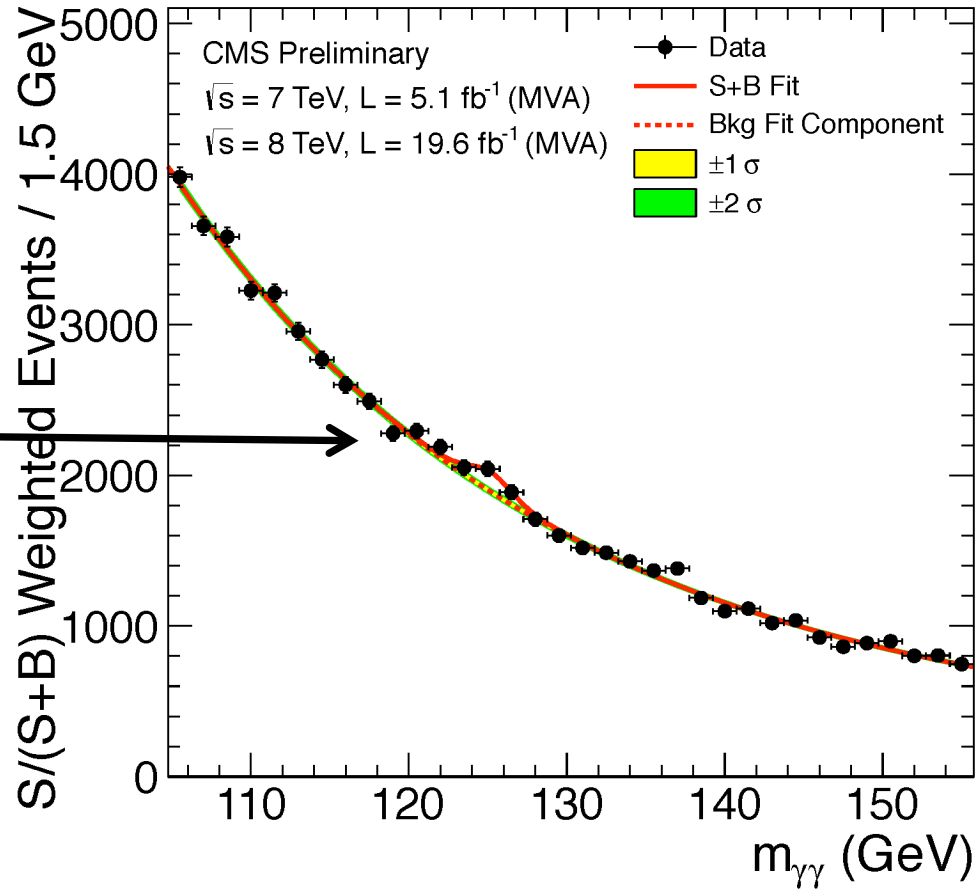
  - VH -> lepton and MET tag to address W->lν, Z->ll and Z->νν decays

8 TeV categories



H→γγ combined mass spectrum

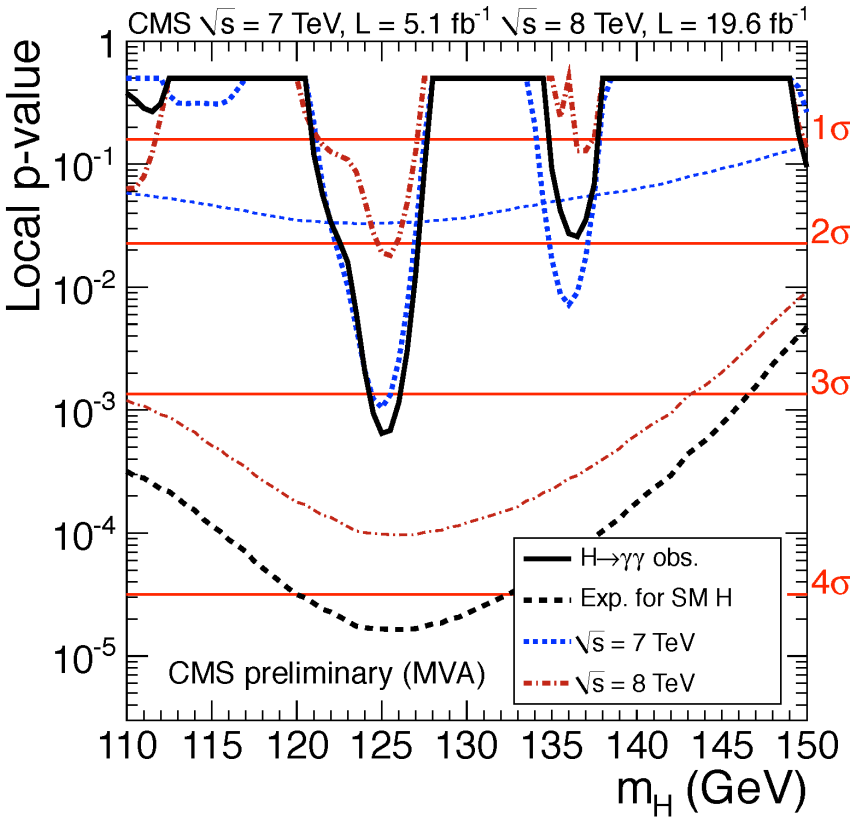
Weighed data events and BG model parametrizations

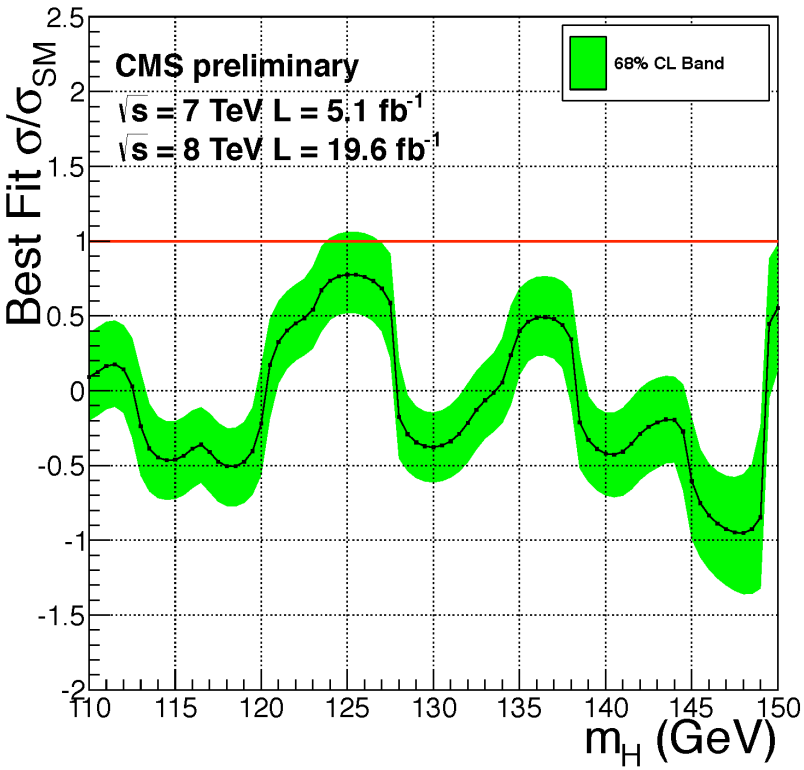


- Sum of mass distributions for each event class, weighted by S/(S+B)
- B is integral of background model over a constant signal fraction interval

- This plot is not used in the analysis and it is for illustration only, it adds all event classes together

H→γγ results: p-values



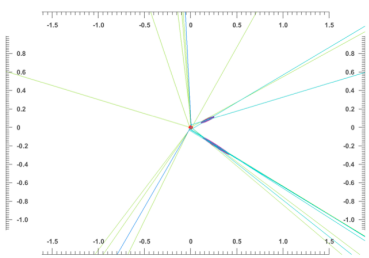


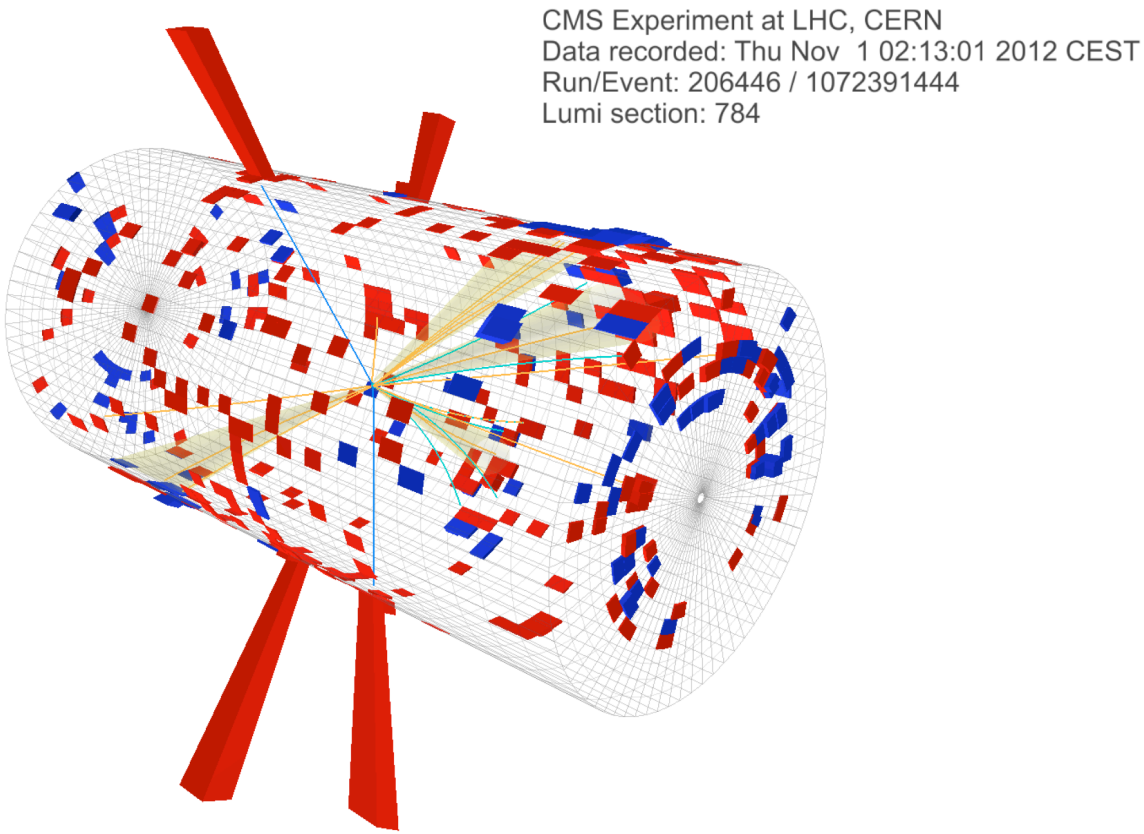
- Largest excess around 125 GeV
  - Local significance 3.2 σ at 125 GeV
  - Expected significance 4.2 σ at 125 GeV
  - Fitted σ/σ_{SM} at 125 GeV $0.78^{+0.28}_{-0.26}$

Consistent results from cut based: σ/σ_{SM} at 125 GeV $1.11^{+0.32}_{-0.30}$

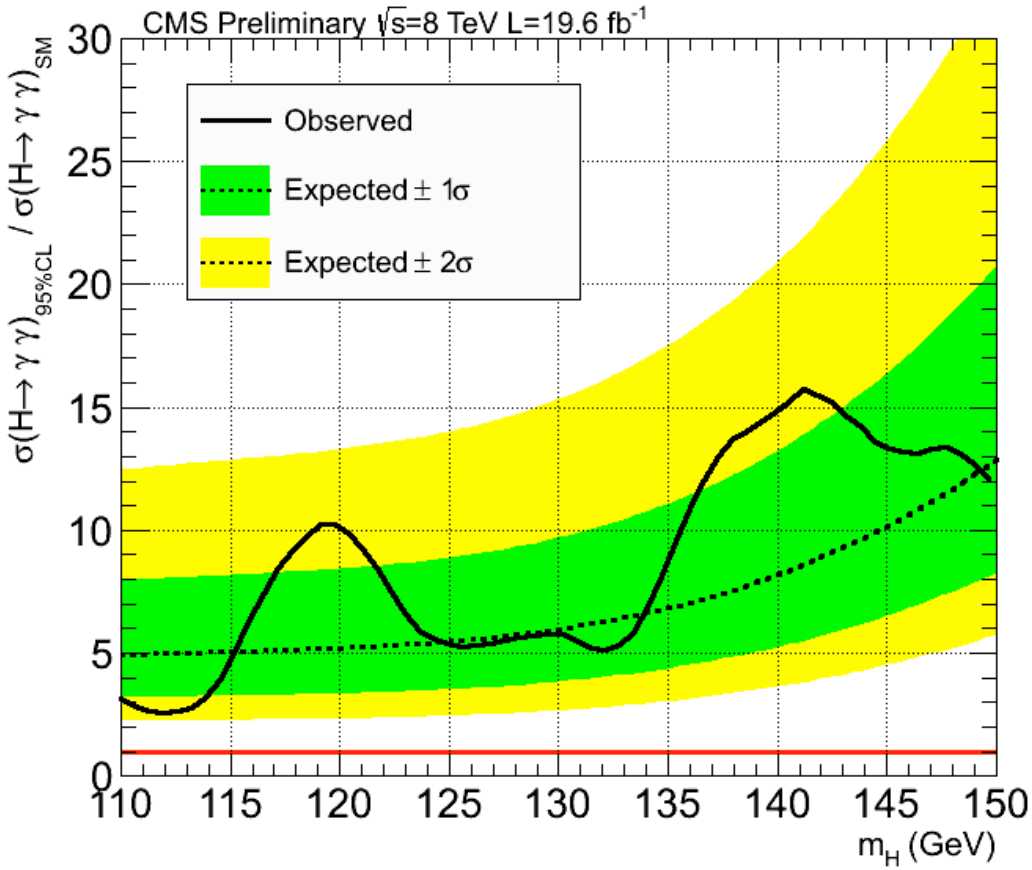
ttH H→γγ

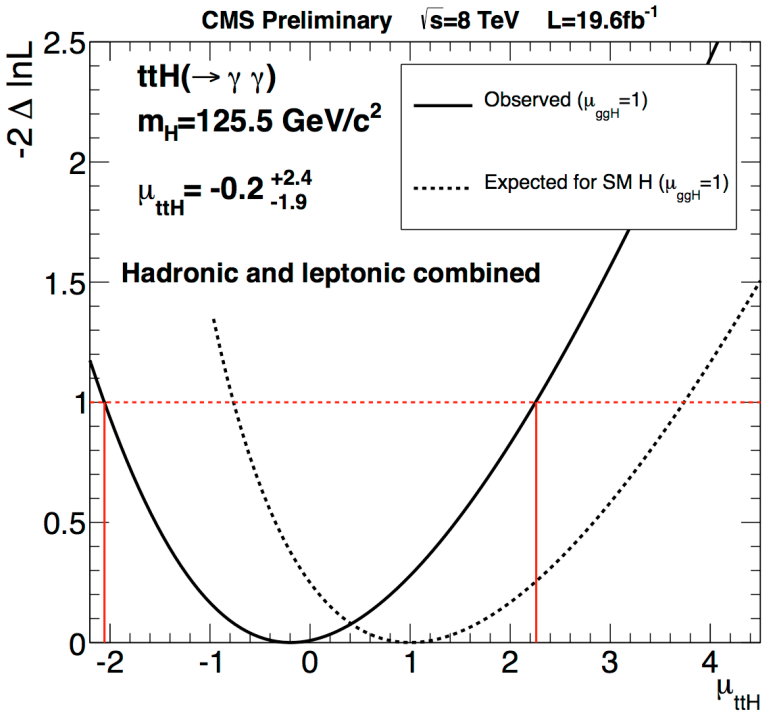
- Channel added more recently
- Not yet part of the overall combination
- Require b-tagging + large jet multiplicity





ttH H→γγ

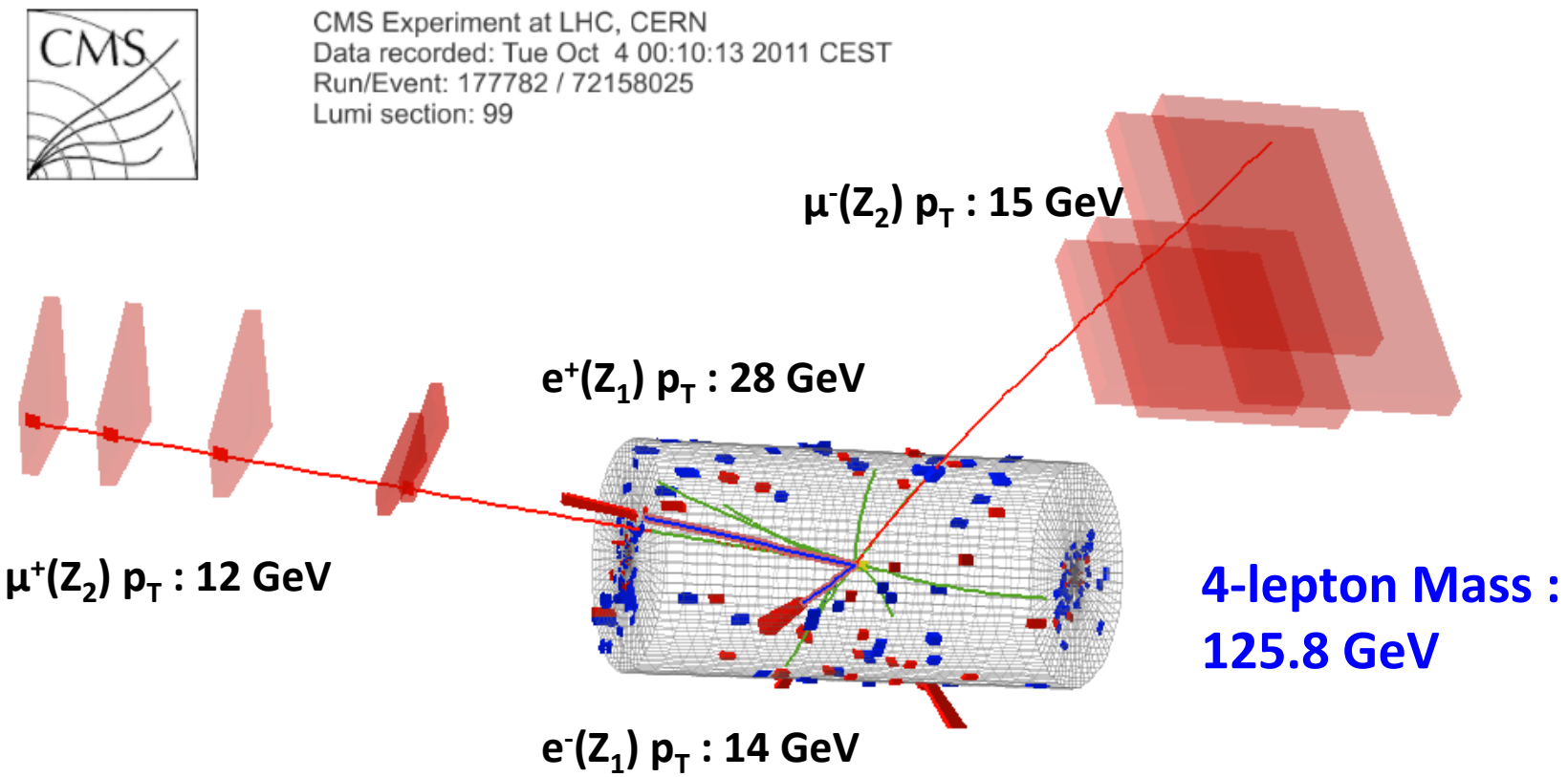




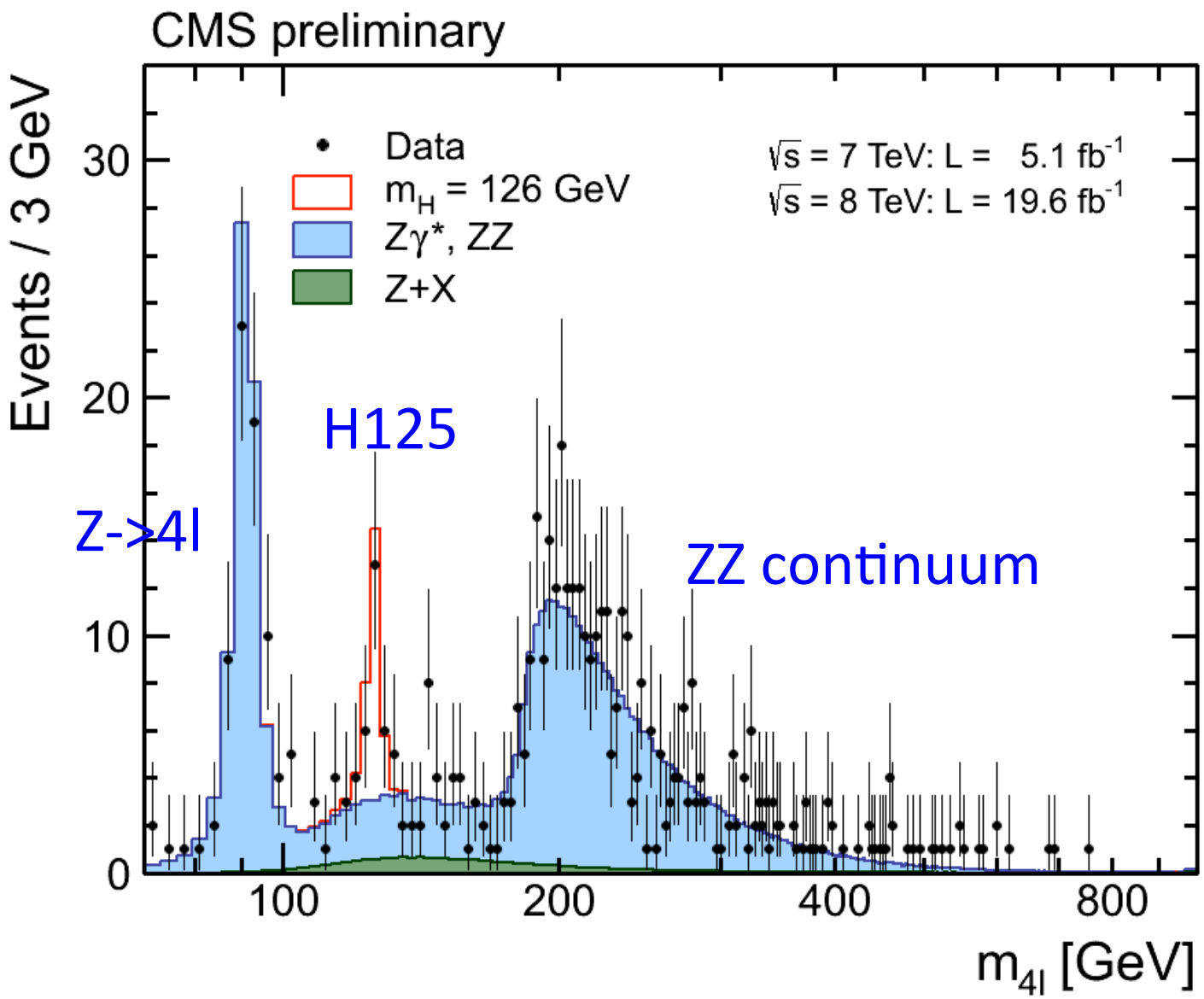
$$\mu_{ttH} = -0.2^{+2.4}_{-1.9}$$

H → ZZ → 4l (4μ, 4e, 2e2μ)

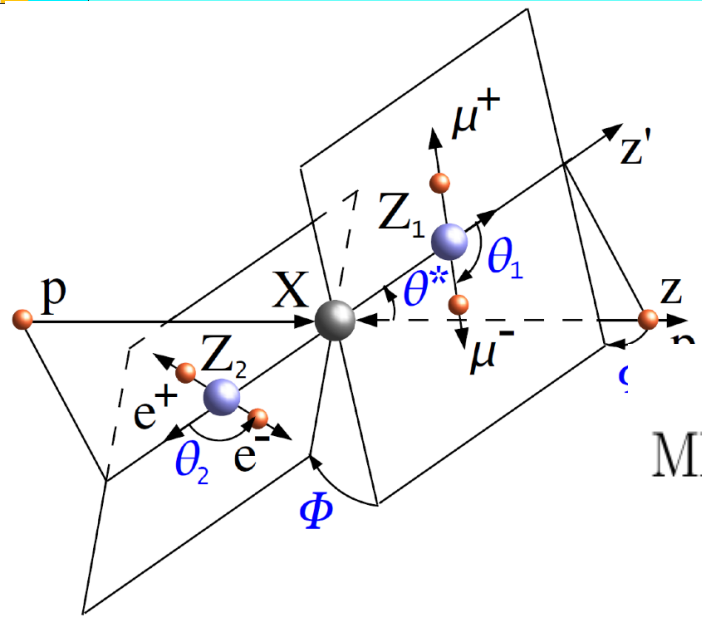
- Clean channel: 2 high mass pairs of opposite sign isolated electrons or muons coming from PV
- **Narrow mass peak**
  - Very good mass resolution 1-2 %
- Background
  - irreducible: ZZ
  - reducible: Z+jets, Zbb, tt, WZ
- Very small BR ~10^{-4} at 125 GeV



H → ZZ → 4l: candidates



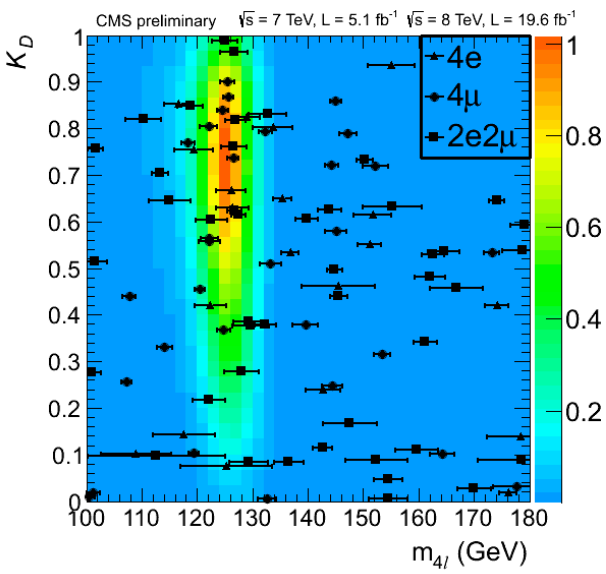
Use other kinematical variables: K_D

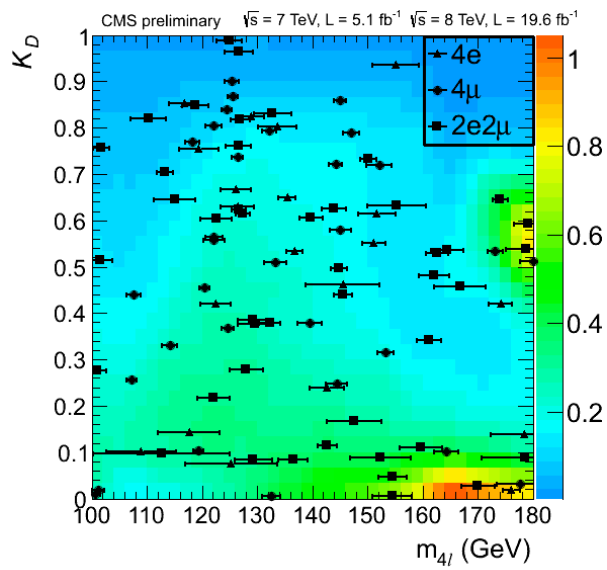


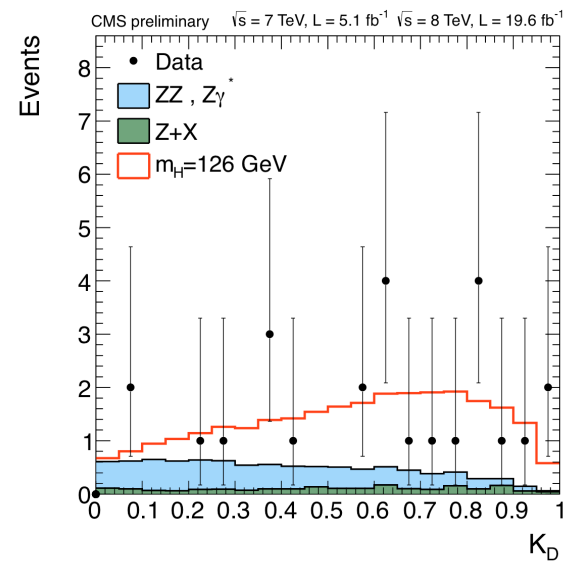
MELA: Matrix Element Likelihood Analysis:
uses kinematic inputs for
signal to ZZ background discrimination
$\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$

$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

M_{4l} = 121.5 – 130.5 GeV



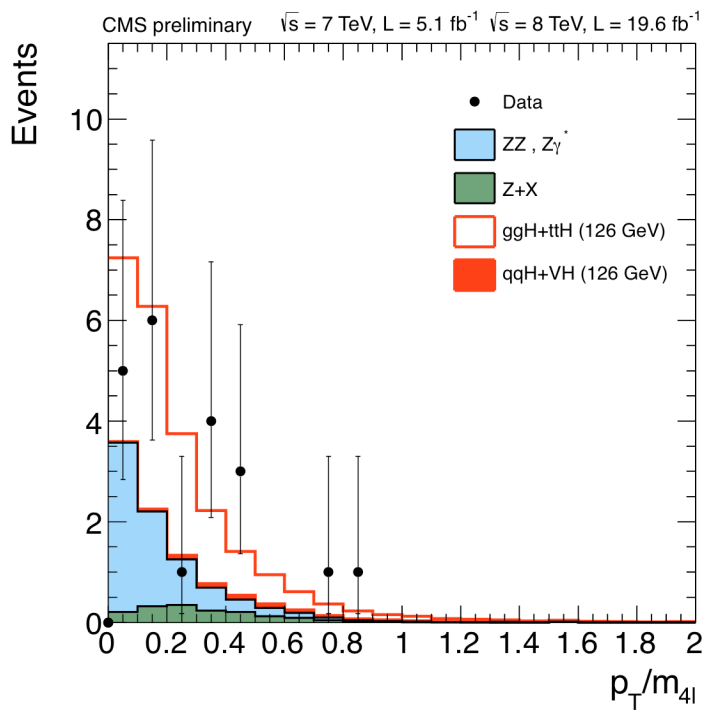


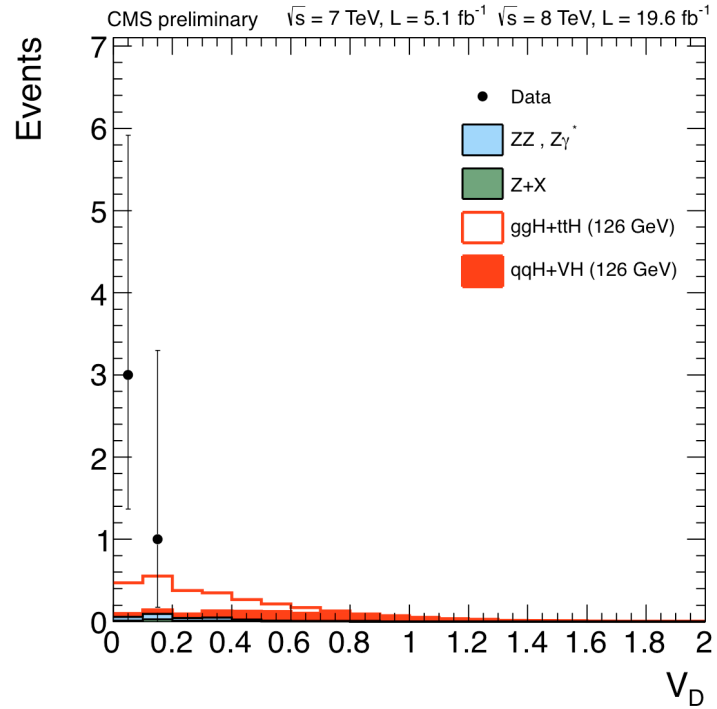


H → ZZ → 4l: fit

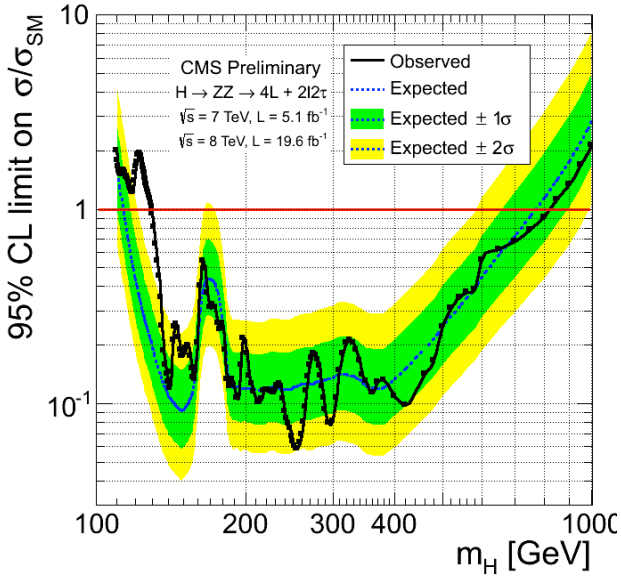
- Add a dijet category
- Use a 3D method
  - Inclusive: Mass – K_D – P_{t4l}
  - dijet category: Mass – K_D– V_D (VBF discriminant)

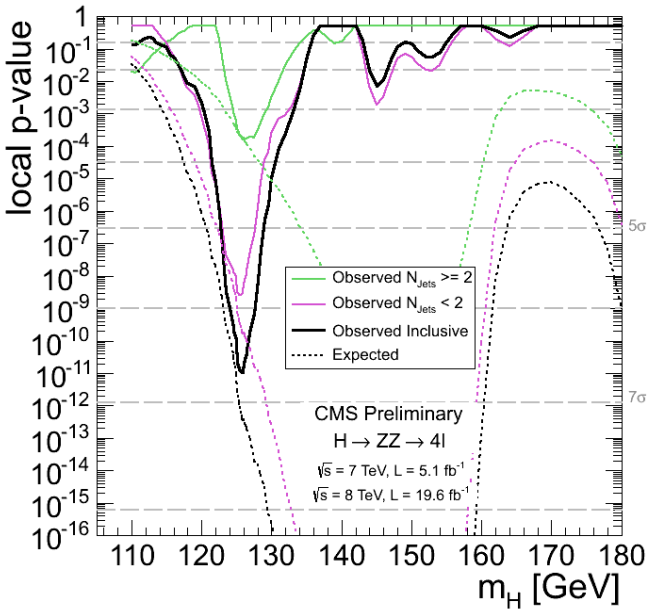
M_{4l} = 121.5 – 130.5 GeV



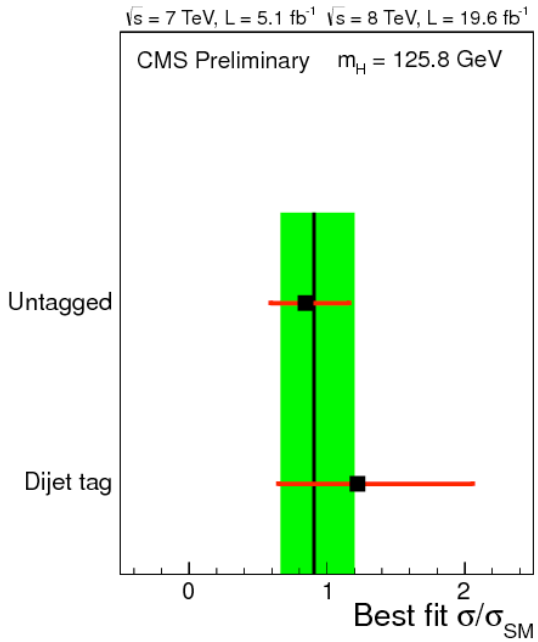


H → ZZ → 4l: results





- Excess of events at 125.8 GeV
  - expected significance: 7.2 σ
  - observed significance: 6.7 σ
  - Fitted $\sigma/\sigma_{SM} = 0.91^{+0.30}_{-0.24}$

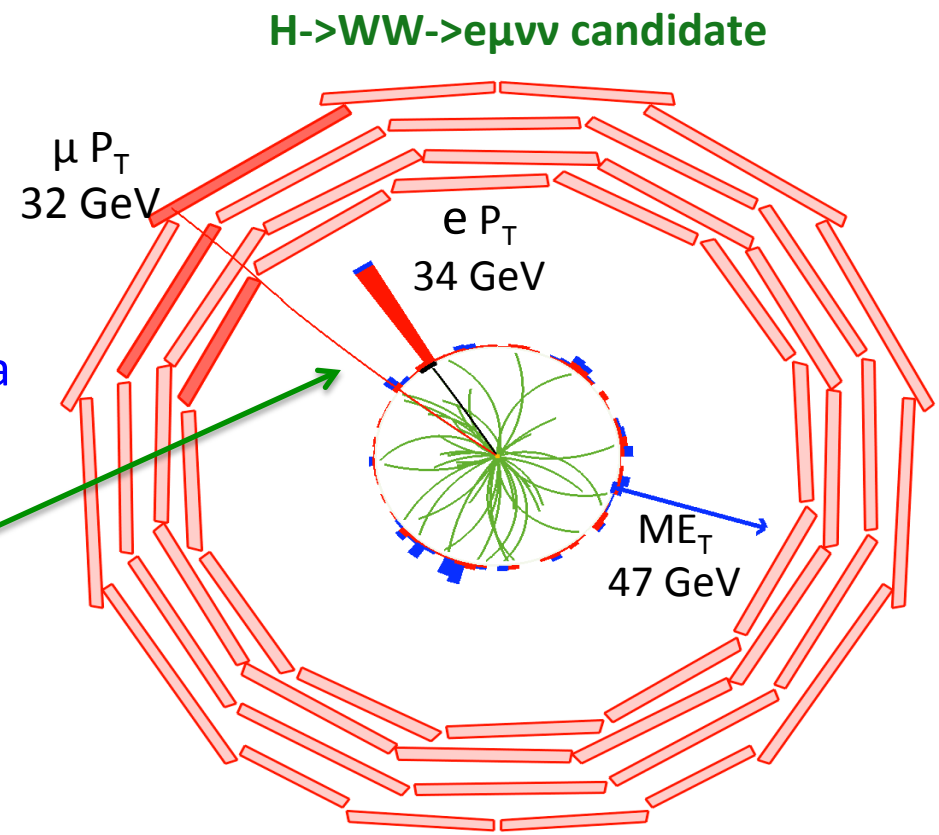


Results from 3D fit,
Consistent results obtained with 1 and 2 D

H→WW→lνlν

- Most sensitive channel around $2xM_W$
  - Also at 125 GeV it gives the smallest error on μ
- **No narrow mass peak (mass resolution ~20%)**
- Two high p_T isolated leptons **+ MET**
- Main backgrounds
  - WW (irreducible)
  - Z+jets, WZ, ZZ, tt, W + jets
- BG estimation is crucial
  - Main BG estimated from data

Scalar Higgs boson +
V-A structure of W decay
favors small opening angle
between the 2 charged
leptons
(tend to have small Δϕ)



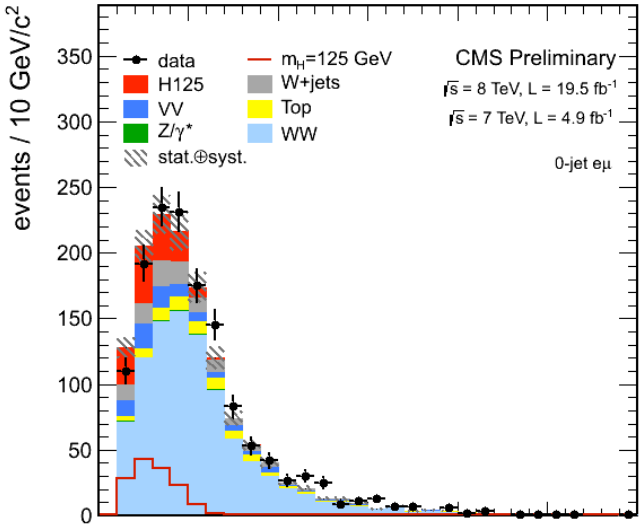
WW→lνlν analysis strategy

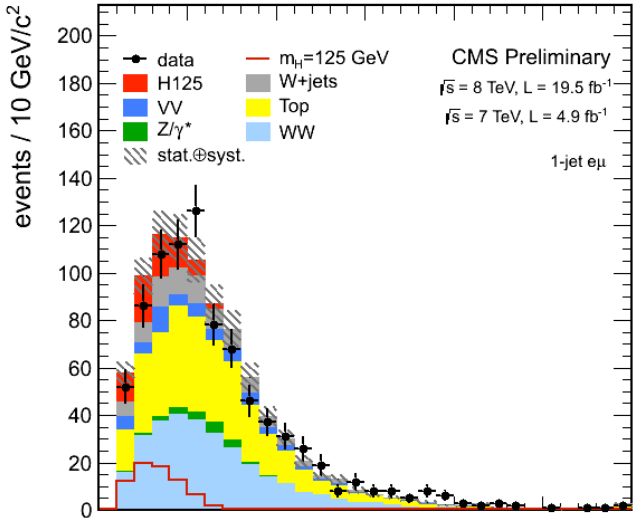
0 Jets (SHAPE)	1 Jet (SHAPE)	2 Jets (Cuts)	Different flavour (eμ)
0 Jets (Cuts)	1 Jet (Cuts)	2 Jets (Cuts)	Same flavour (ee, μμ)

- Same flavour has larger BG that is harder to model (cut based analysis used)
- 2 jet bin corresponds to VBF dijet tag
- 0 and 1 jet different flavour (most sensitive) use 2D shape analysis in M_{ll}, M_T variables

$$M_T = \sqrt{2 p_T^{\ell\ell} E_T^{miss} (1 - \cos \Delta\phi_{E_T^{miss}\ell\ell})}$$

2012 data: cut based analysis at 8 TeV



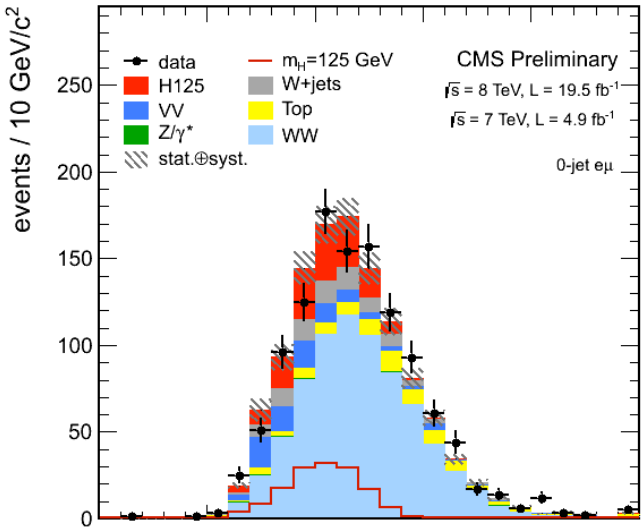


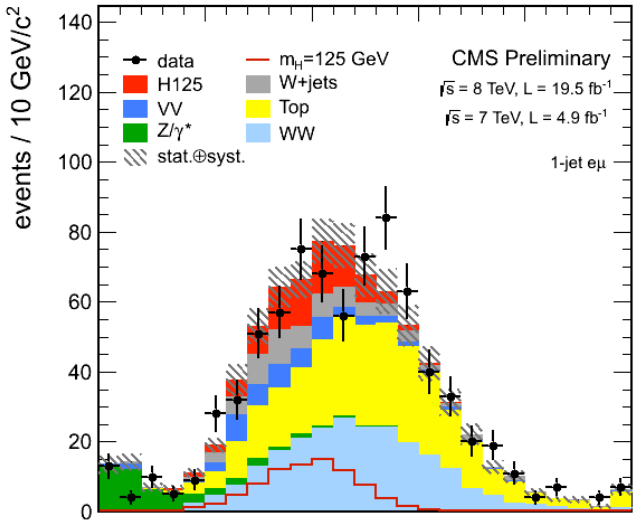
0-jet bin combined

M_{ll} (GeV)

M_{ll} (GeV)

1-jet bin combined



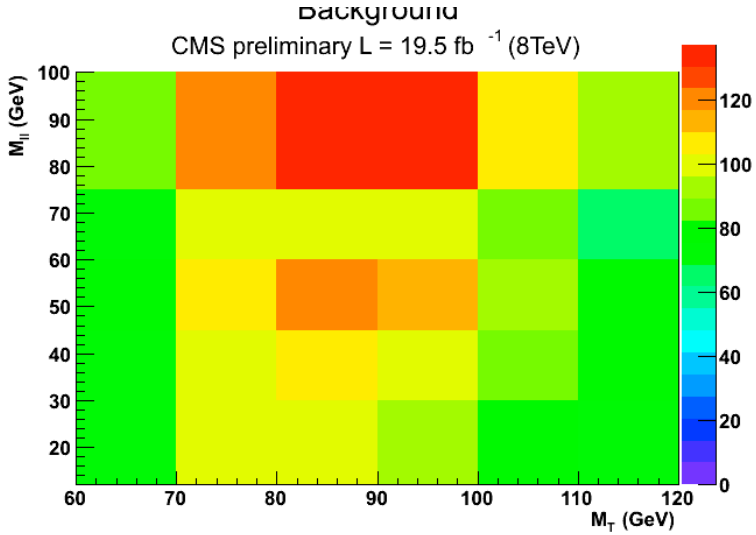


M_T (GeV)

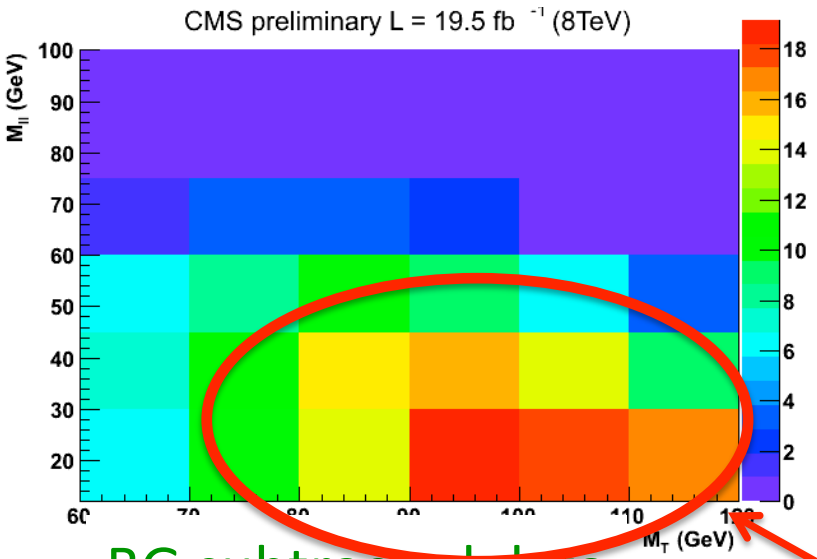
M_T (GeV)

WW→lνlν 2D analysis (0 jet bin)

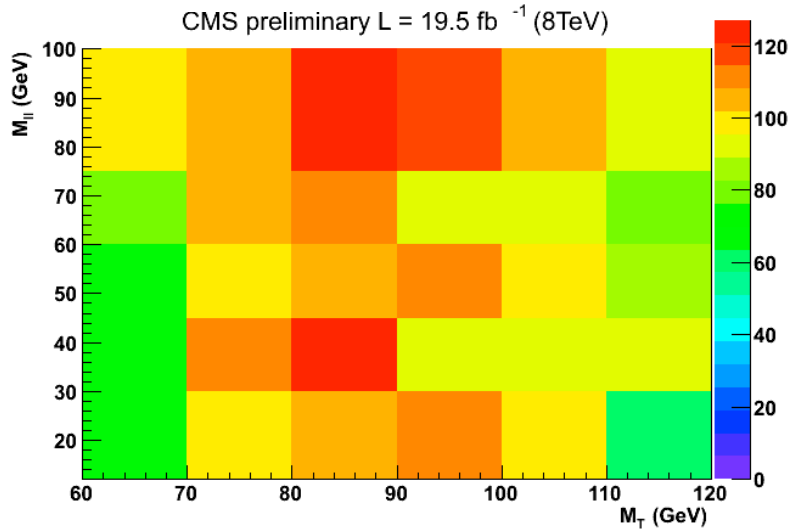
MC Background



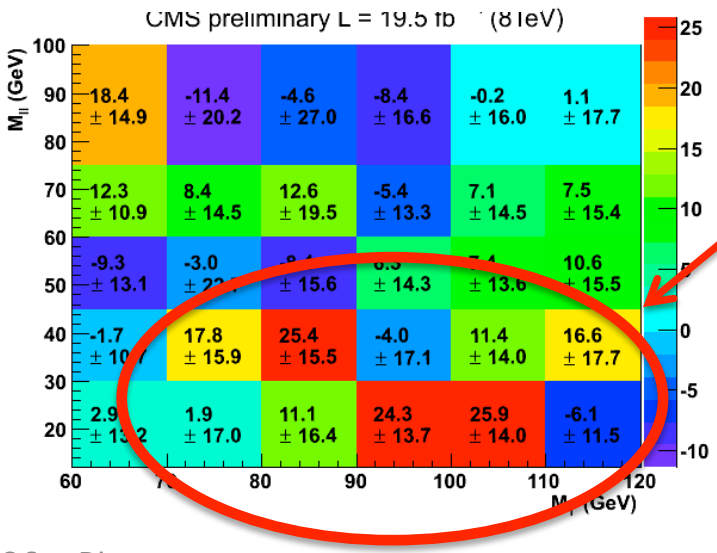
Higgs signal at 125 GeV



Data

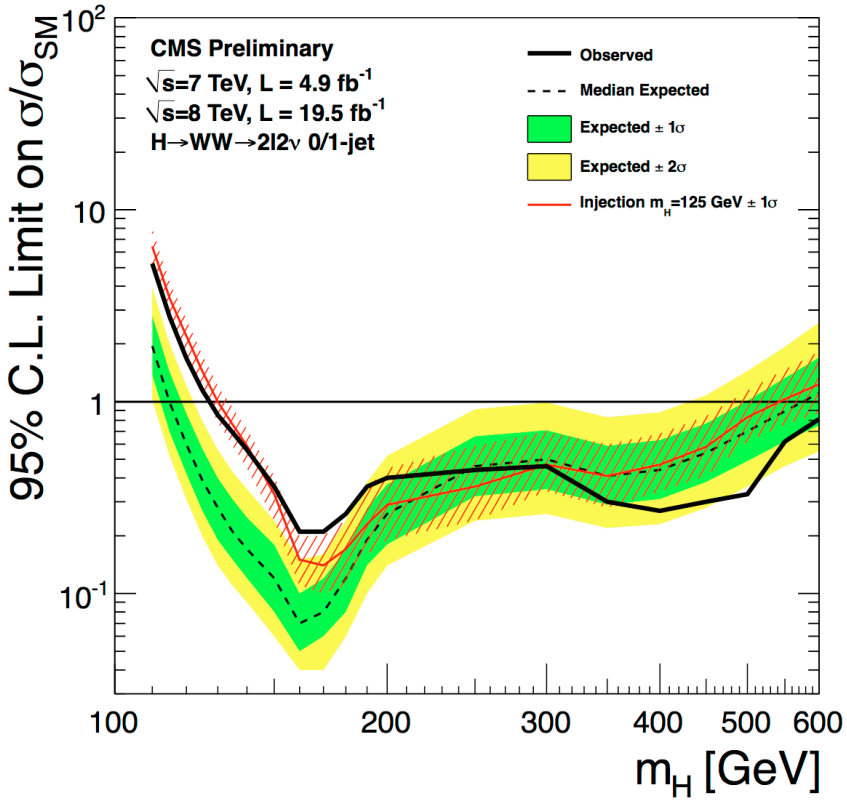


BG subtracted data

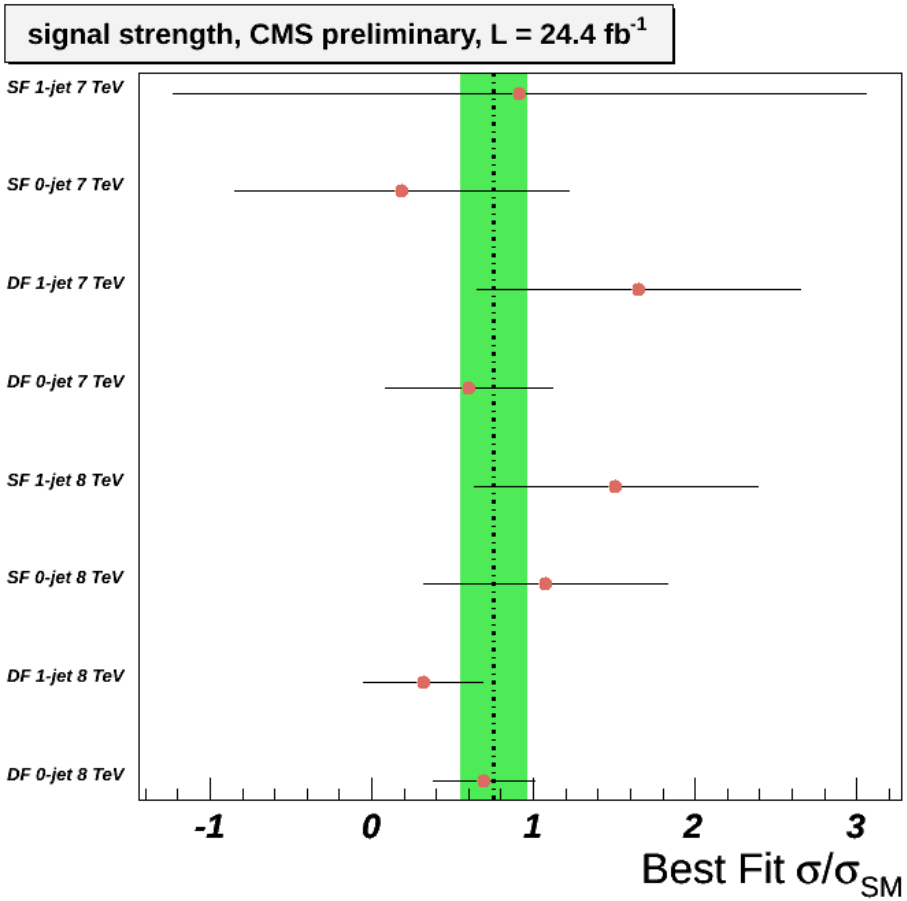


Signal region

H→WW→lνlν: results



Channel compatibility plot



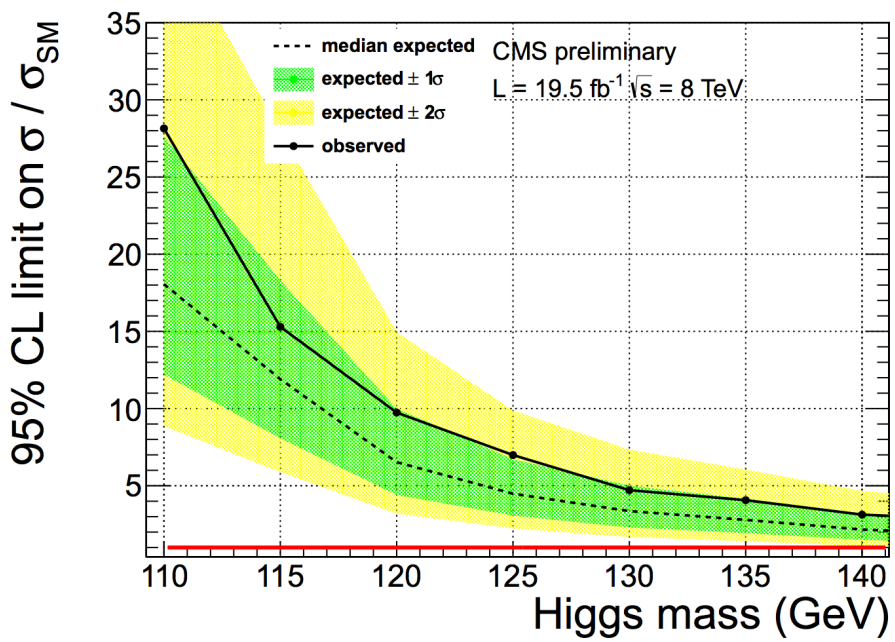
- Broad excess around 125 GeV
  - expected significance: 5.1 σ
  - observed significance: 4.0 σ
  - Fitted $\sigma/\sigma_{SM} = 0.76 \pm 0.21$

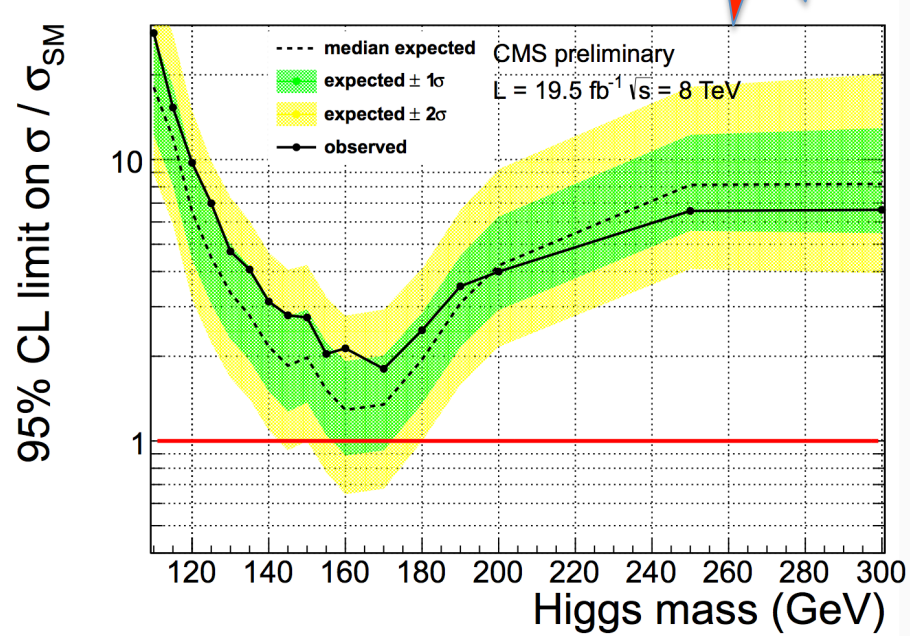
VH: H→WW→2l2ν and V→jj

- Similar analysis as dijet WW→2l2ν with two central jets with mass consistent with W or Z

NEW

CMS PAS HIG-13-017





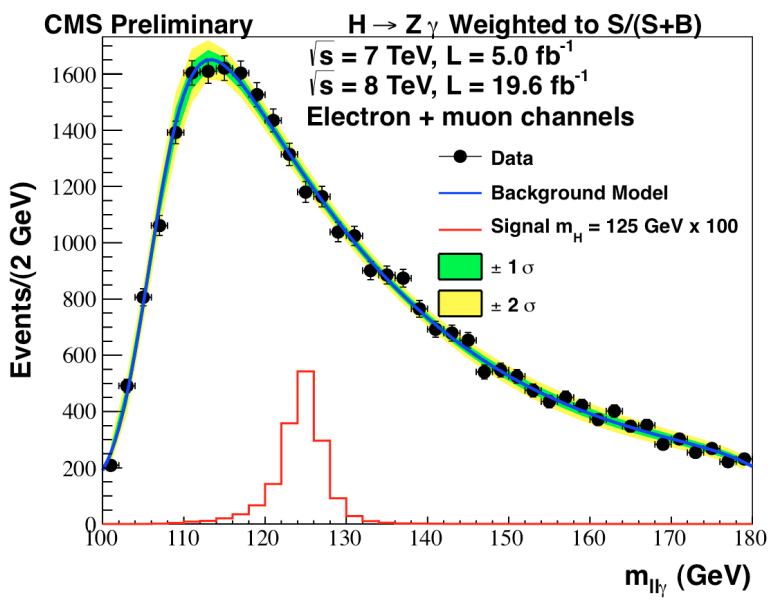
95% exclusion on μ At 125 GeV
Expected 4.7
Observed 6.7

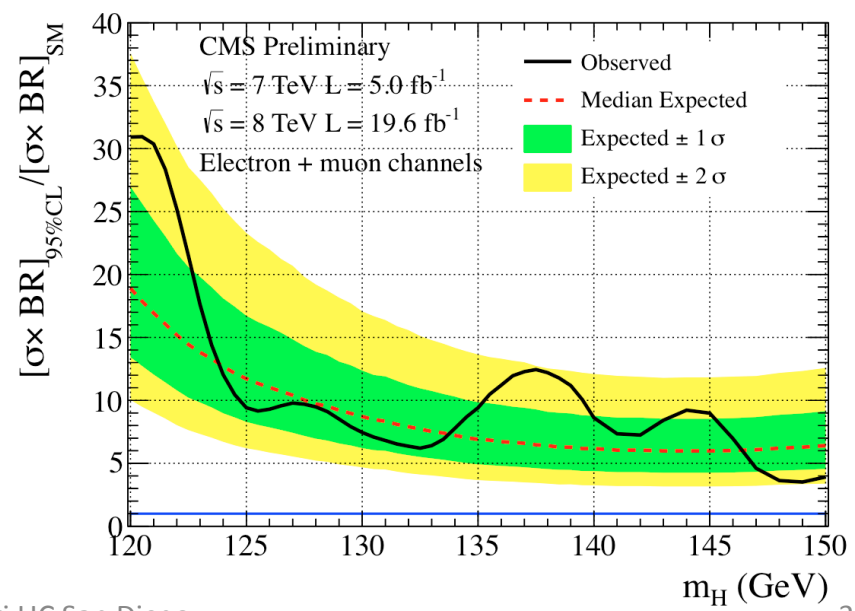
H→Zγ

- Cross section similar to γγ
- Use Z->ee and Z->μμ (reduce cross section)
- Large BG from Drell Yan with ISR

Models exist with BR(Zγ) >100 x SM while BR(γγ) is SM-like

Sample	Luminosity (fb^{-1})	num. of events $100 < m_{\ell\ell\gamma} < 180$ GeV	num. of events $120 < m_{\ell\ell\gamma} < 150$ GeV	num. of events predicted for $m_H = 125$ GeV
2011 ee	4.98	2268	1041	1.2
2011 $\mu\mu$	5.05	2739	1223	1.4
2012 ee	19.62	12482	5534	6.3
2012 $\mu\mu$	19.62	13392	5993	7.0





Fermionic decay channels

- $H \rightarrow \tau\tau$
- $H \rightarrow bb$

H→ττ analysis

- Complicated analysis, many different sub-channels

Decay

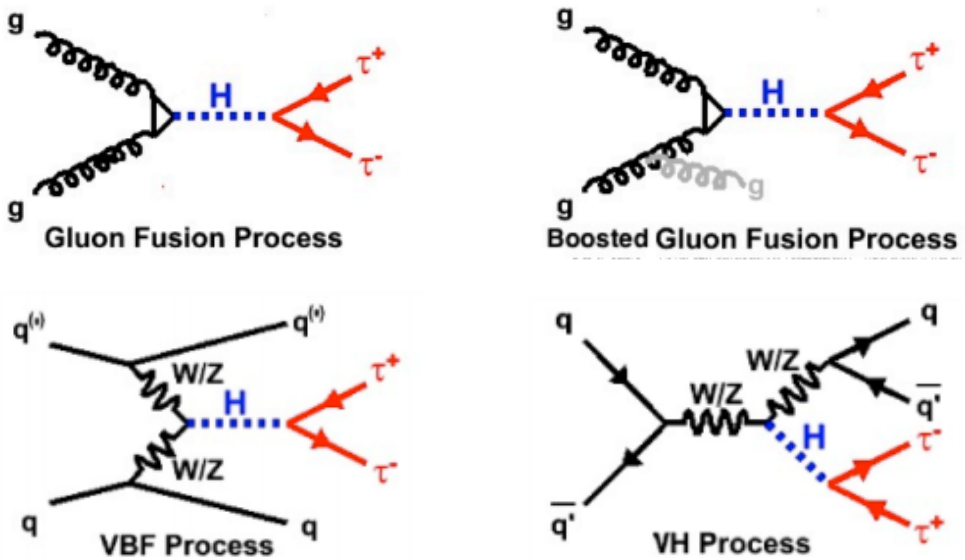
$$H \to \tau\tau \to \ell\ell + 4\nu \ (12\%)$$
$$H \to \tau\tau \to \ell\tau_h + 3\nu \ (46\%)$$
$$H \to \tau\tau \to \tau_h\tau_h + 2\nu \ (42\%)$$

$\otimes$

Production/signature

0-jet
1-jet boosted
2-jet VBF
VH (use leptonic decays of V)

Also split e and μ in the analysis



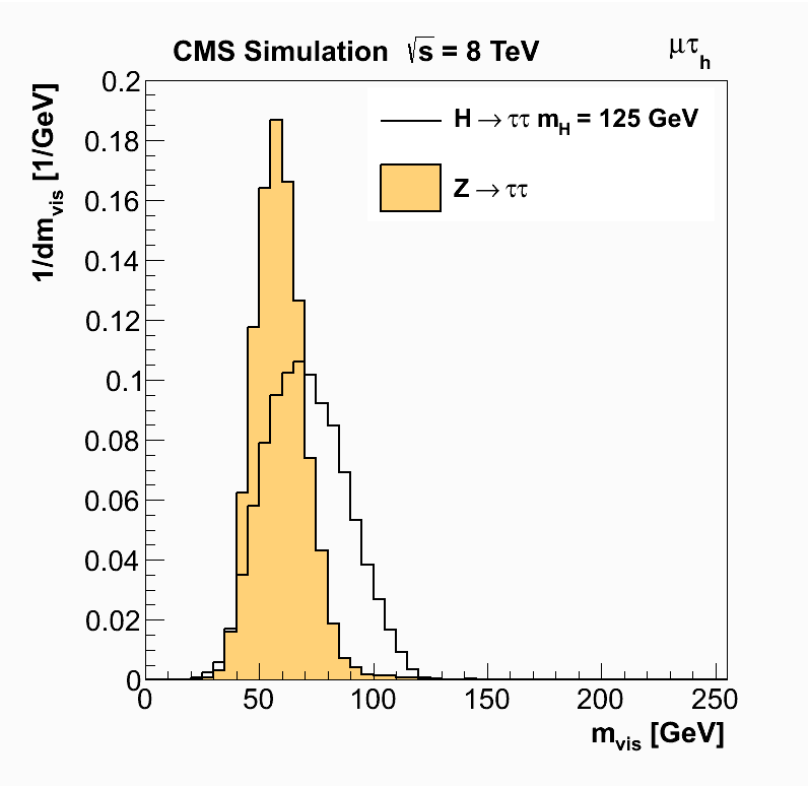
- Z->ττ main BG (also W +jets, tt and QCD)
- 0-jet category only kept to fit BG normalization

- All categories are fitted simultaneously
- Also important for MSSM

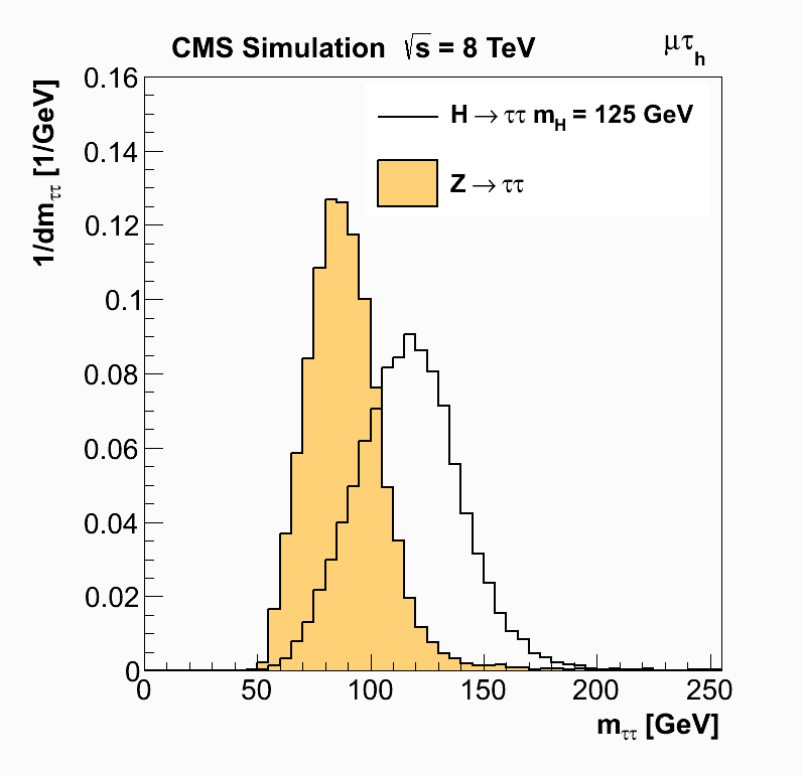
H→ττ mass

- Invariant mass calculation
  - Use full kinematical fit
  - Mass resolution: 15-20%

Visible mass

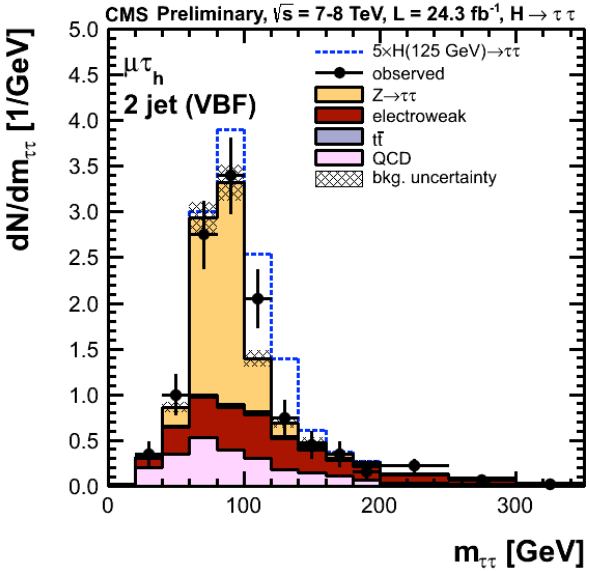


Fitted mass

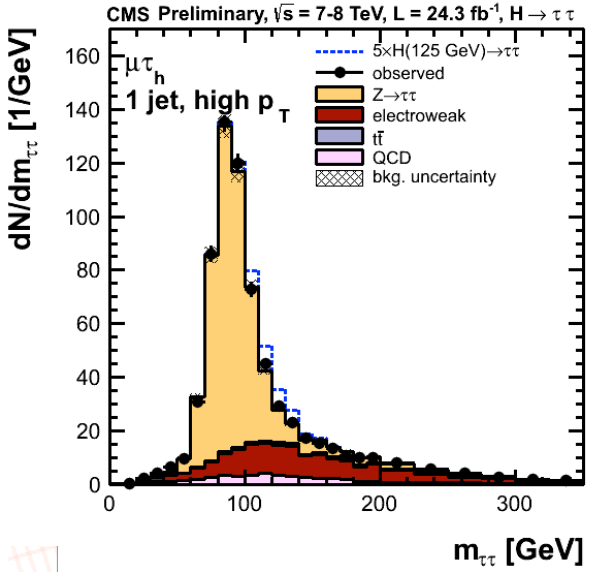


H→ττ: analysis

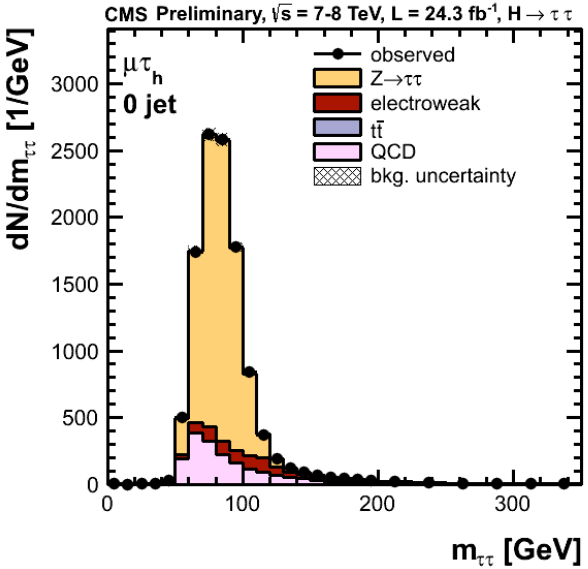
$\mu\tau_h$ VBF

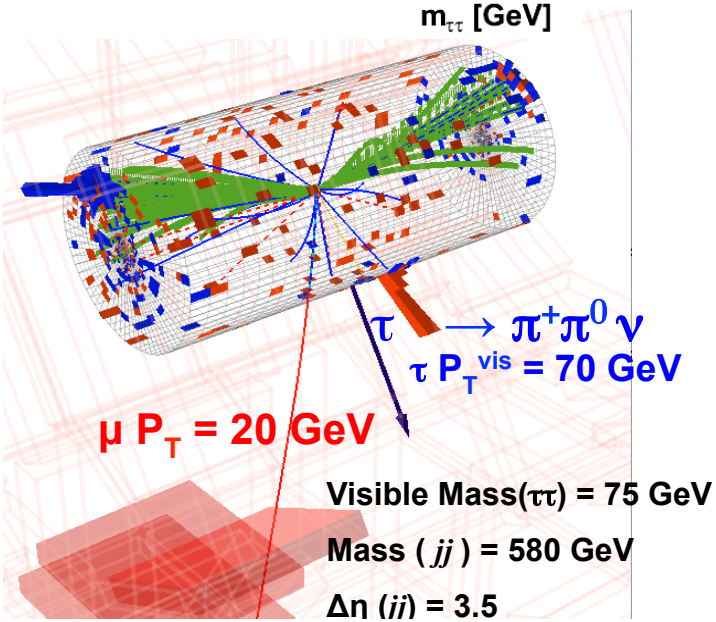


$\mu\tau_h$1-jet



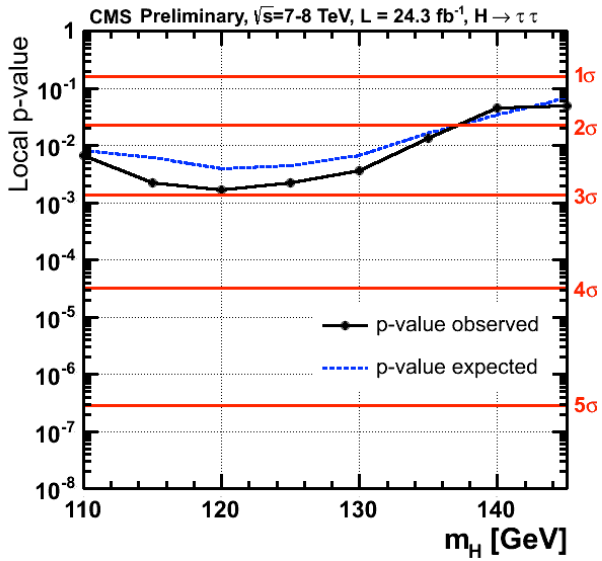
$\mu\tau_h$0-jet



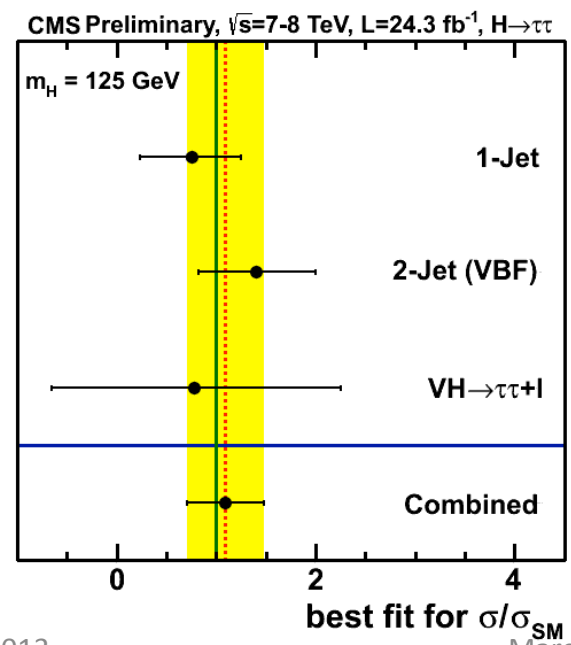


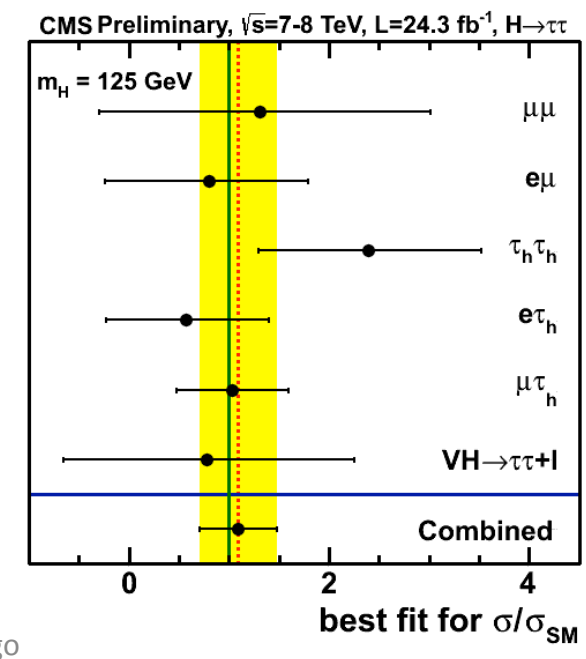
All categories are fitted simultaneously

H→ττ: results



- Excess of events near 125 GeV
  - expected significance: 2.62 σ
  - observed significance: 2.85 σ
  - Fitted $\sigma/\sigma_{SM} = 1.1 \pm 0.4$

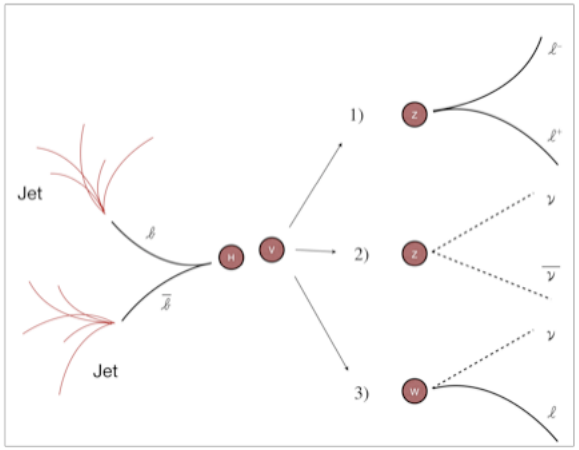




H→bb channel

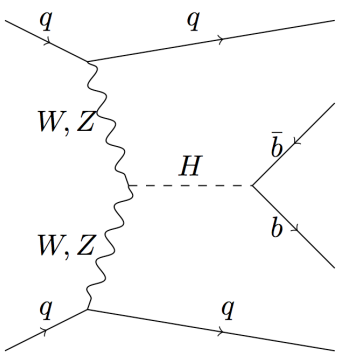
- QCD BG too large for gg fusion, needs additional tag
- Exploit all other production channels

VH

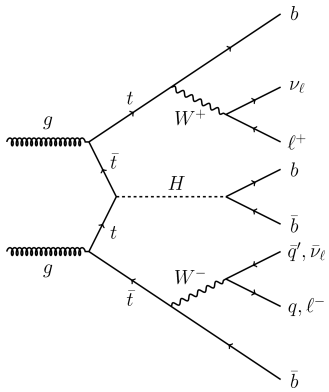


W→e,μ, Z→ee,μμ,νν

VBF

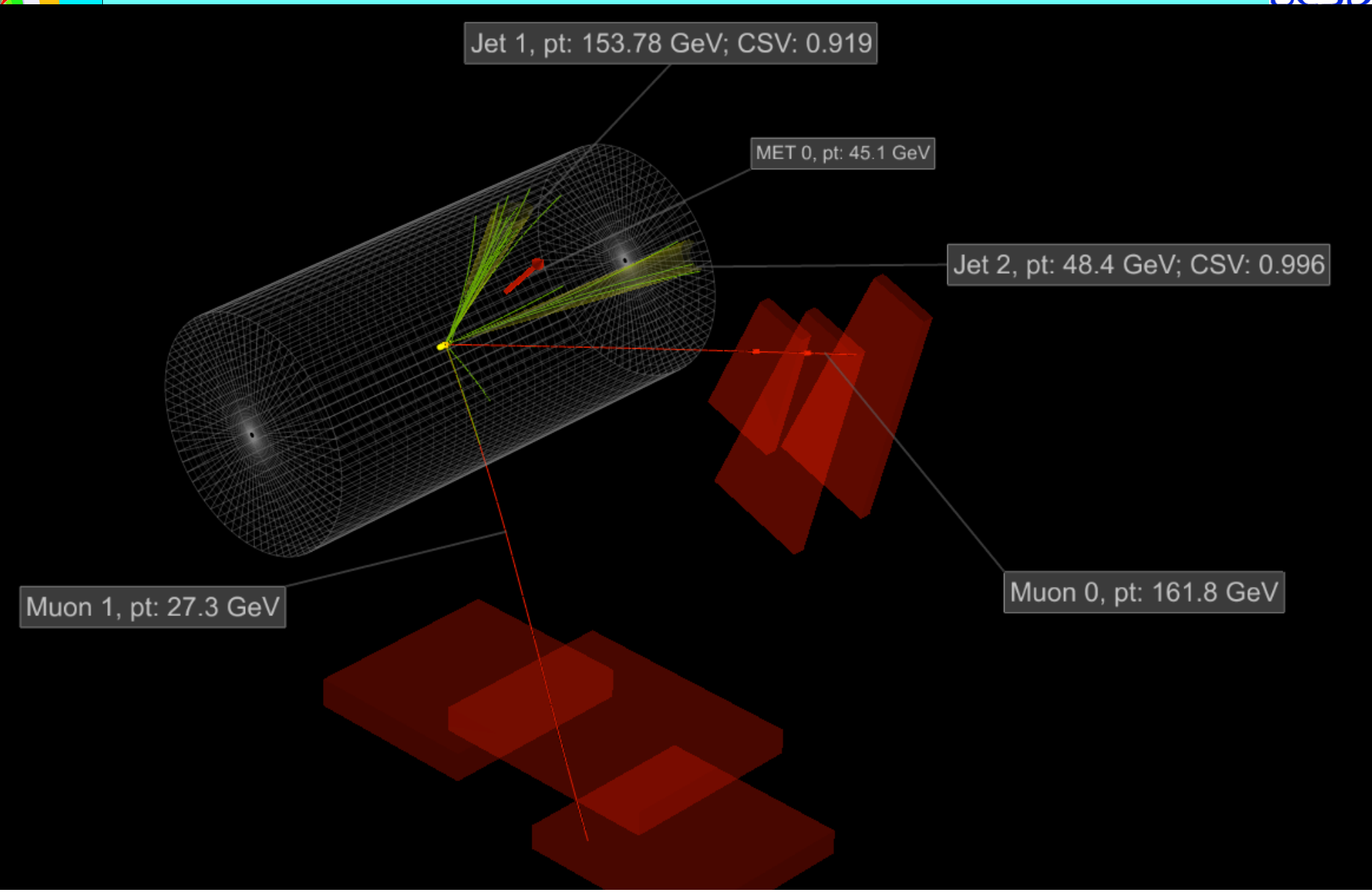


ttH



- Common features:
  - B-tagging
  - bb mass reconstruction, use BDT regression (σ_M/M = 8-9%)
  - MVA based analyses to enhance the sensitivity

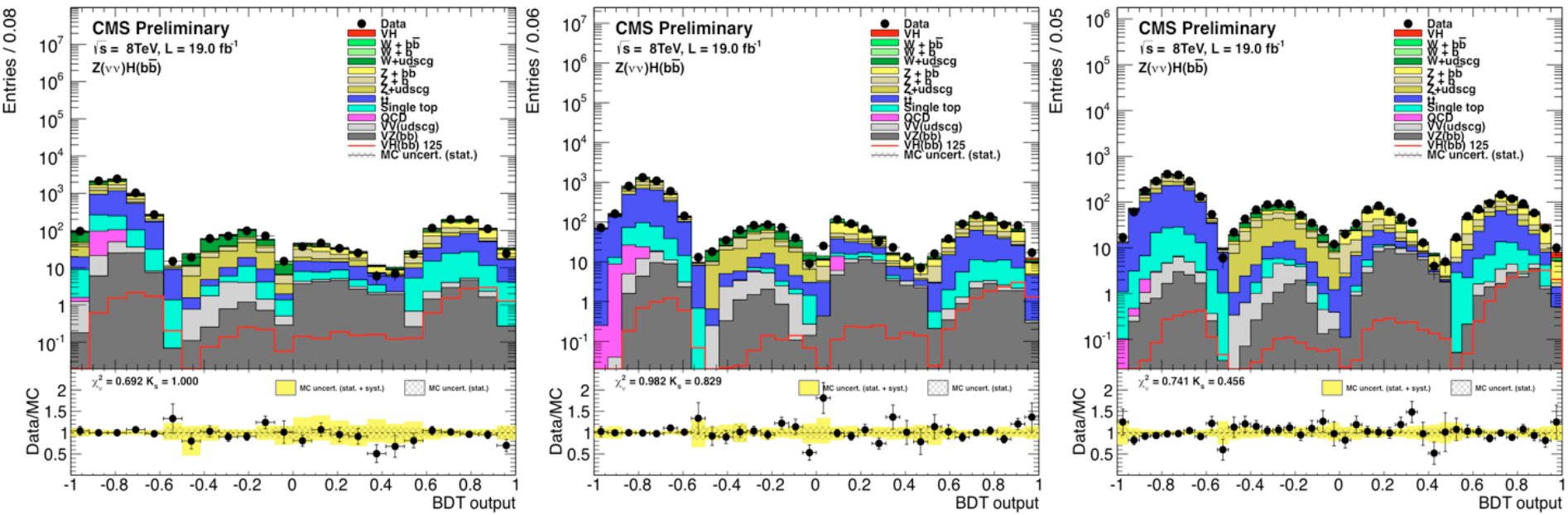
VH→μμbb candidate



H→bb: MVA shape analysis

- Use shape analysis with MVA discriminator with input variables: jet kinematic variables, b-tag variables, …
- Also split according to MVAs trained to select different BG
- Like for H->ττ carry out simultaneous fit to all channels

Z->νν, low p_T^{bb} **Z->νν, medium p_T^{bb}** **Z->νν, high p_T^{bb}**

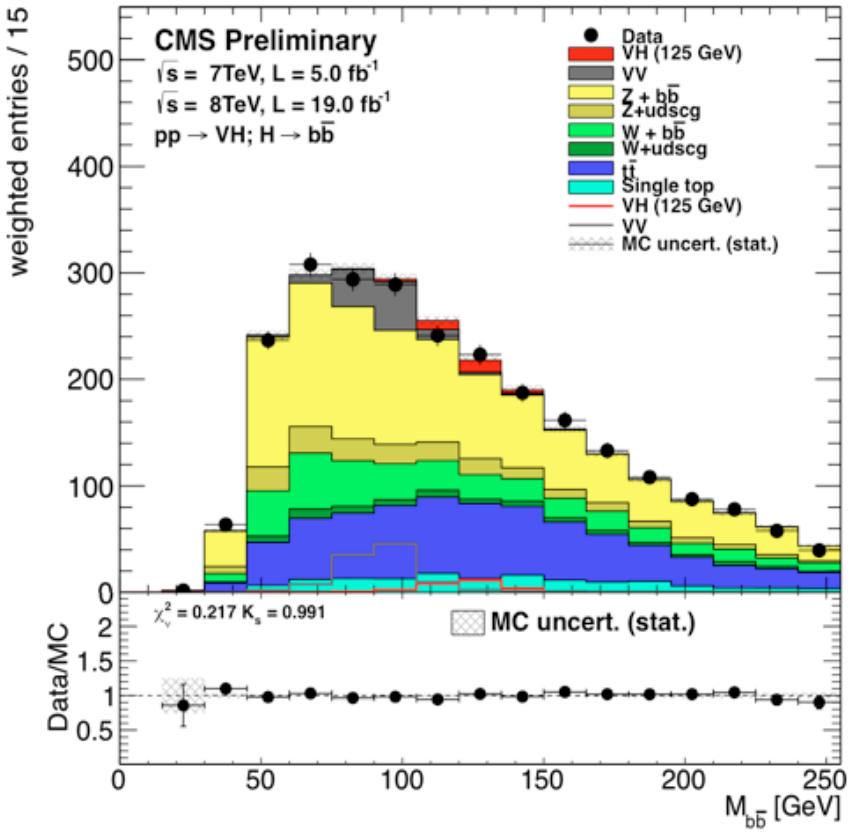


4 sub-regions are enriched in:

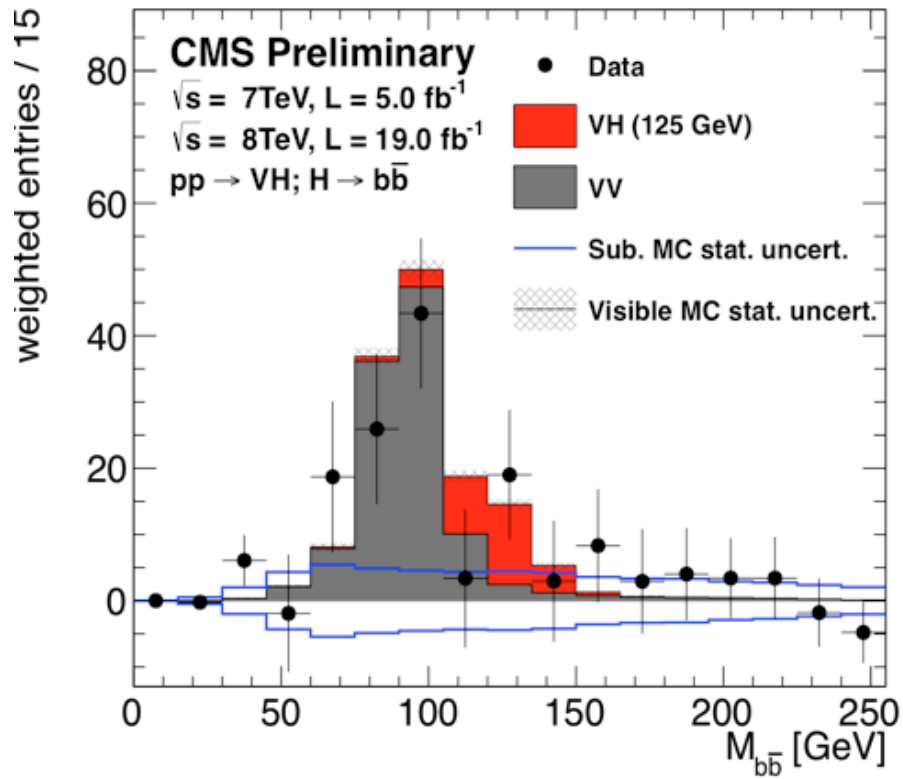
tt̄ V + jets VV VH

Combined plot weighted by S/(S+B)

s/b weighted mass distribution



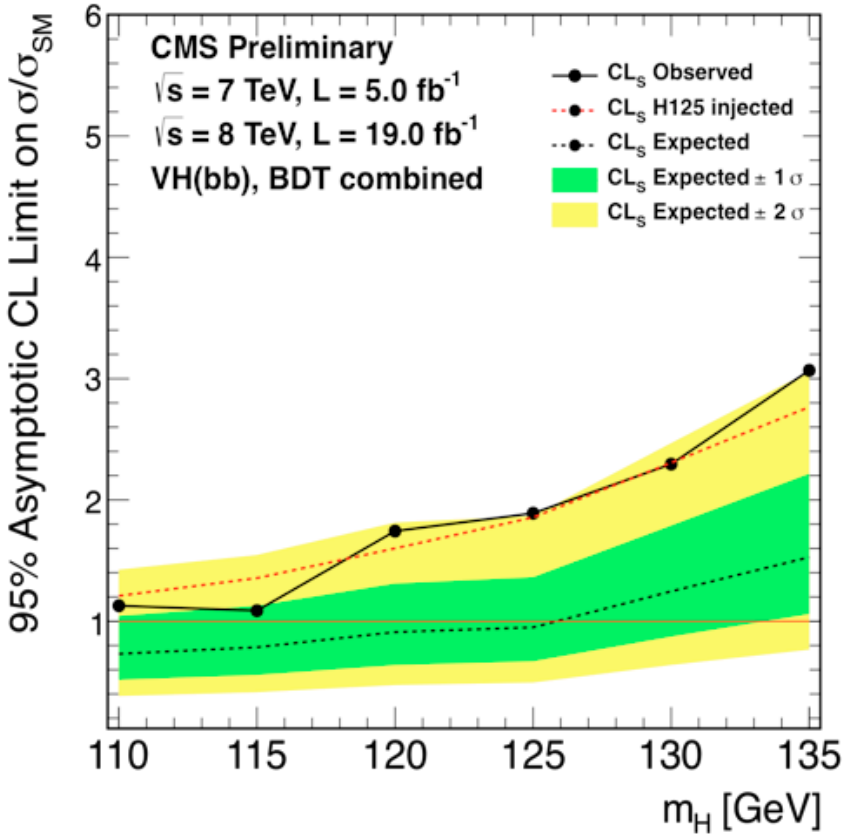
BG subtracted (except VV)

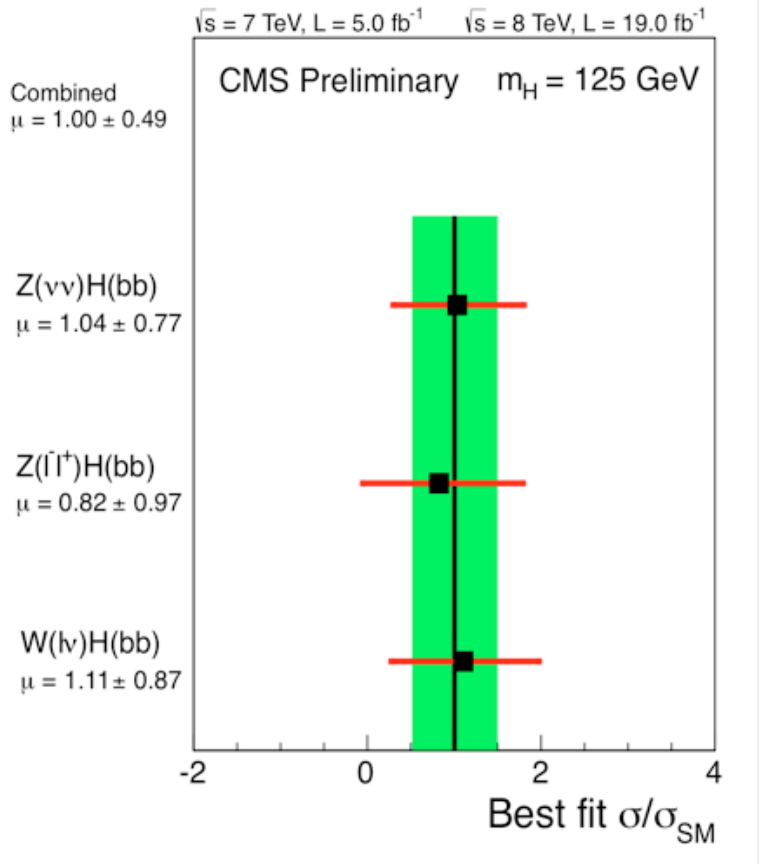


Dibosons, mainly ZZ and WZ with Z->bb

Higgs signal

VH with H→bb: results





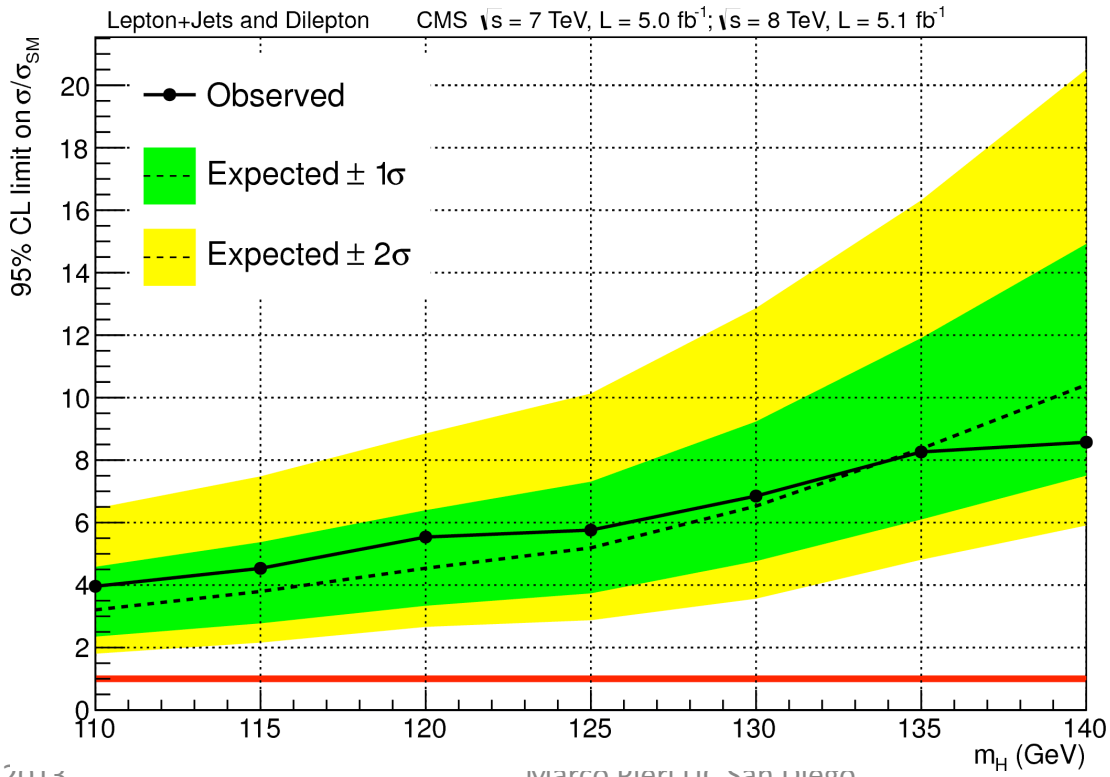
- Excess of events near 125 GeV
  - expected significance: 2.1 σ
  - observed significance: 2.1 σ
  - Fitted $\sigma/\sigma_{SM} = 1.0 \pm 0.5$

Combined with H->ττ gives 3.4 σ significance of fermionic Higgs decays

ttH with H→bb

- Use semileptonic and dilepton tt decays
  - ttH→lvjjbb and ttH→lvlvbb
- Shape analysis using MVA (Neural Network) with simultaneous fit of different jet and b-tag multiplicities

5+5 fb^{-1}
Not yet updated with full statistics

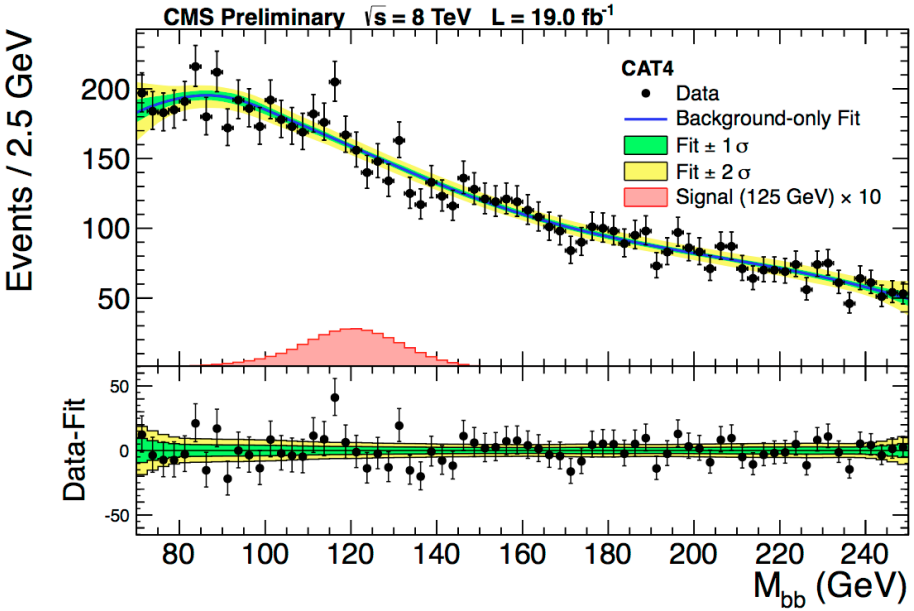


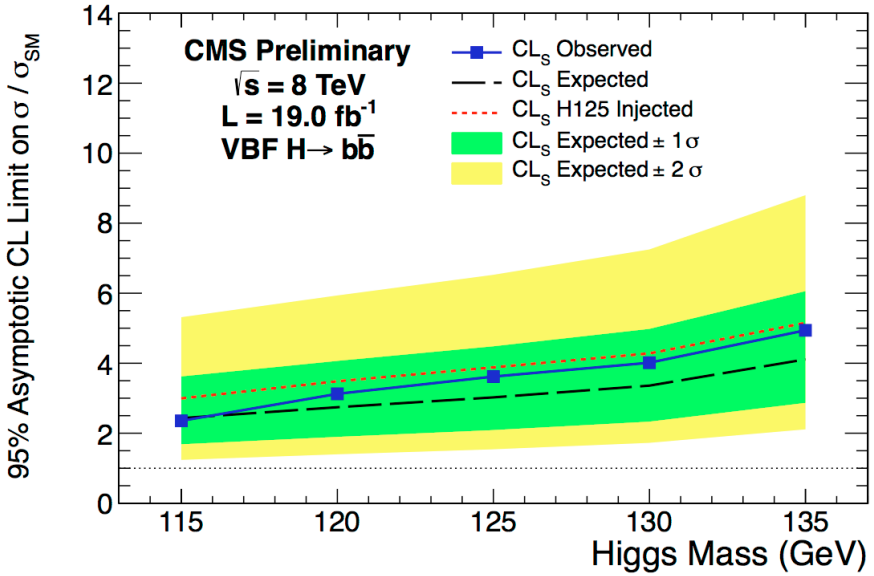
95% exclusion on μ
At 125 GeV
Expected 5.2
Observed 5.8

VBF production with H→bb channel

- Selection based on MVA
- Mass shape analysis with BG fitted from the data (same method as H->γγ analysis)

Most sensitive category





Fitted $\sigma/\sigma_{SM} = 0.7 \pm 1.4$

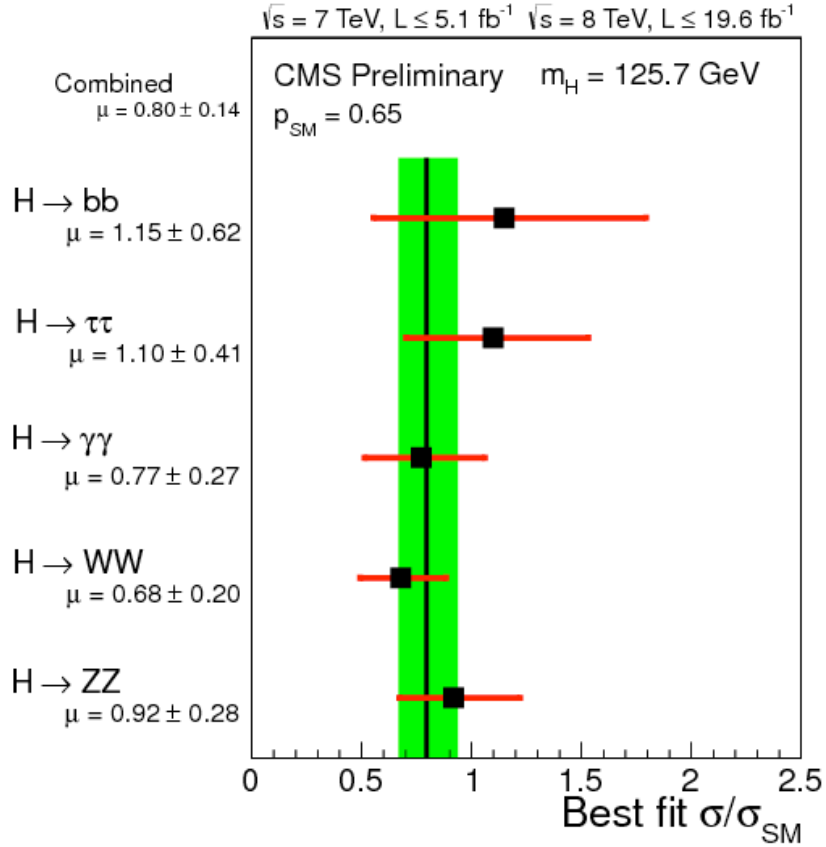
H125 Higgs boson properties

- All channels are combined
- Profile likelihood fits are carried out with all nuisances profiled
- For confidence level estimation asymptotic CLs and p-values are used
- Combination methods are described in:
  - ATL-PHYS-PUB/CMS NOTE 2011-11, 2011/005, (2011)

- Cross sections, BR and recommendations taken from the LHC cross section WG:
  - https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

Combined signal strength

Comparison of channels for M_H=125.7 GeV

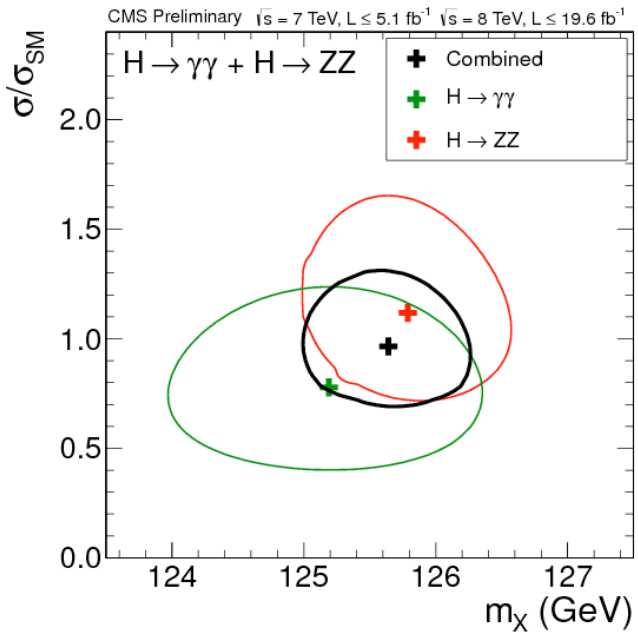


- The fitted μ of the excess near 125 GeV is consistent with the SM scalar boson expectation:
  - σ/σ_{SM} = 0.80±0.14
- Signal strengths in different channels are consistent
- Common cross section theoretical errors contribute to all measurements
  - dominated by 15% error on gg-fusion where applicable

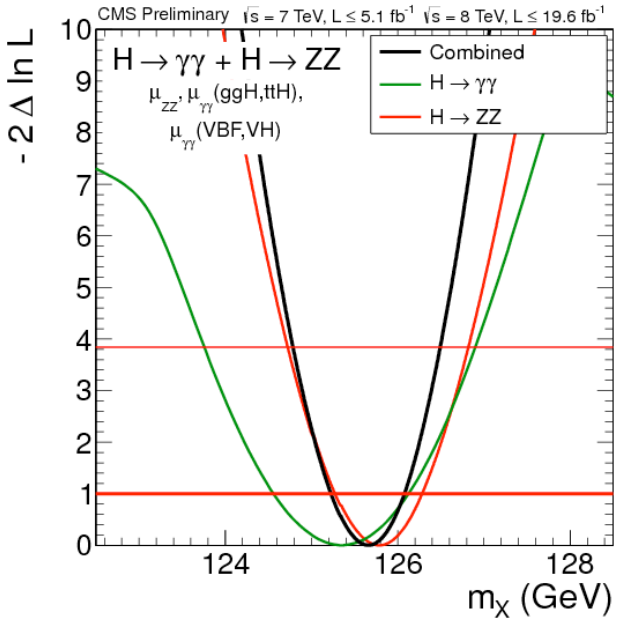
Mass measurement

- Mass can be measured with higher precision with γγ and ZZ
  - To reduce model dependence, allow for free cross section in different channels and fit for the common mass

2D scan μ vs mass



1D scan: mass

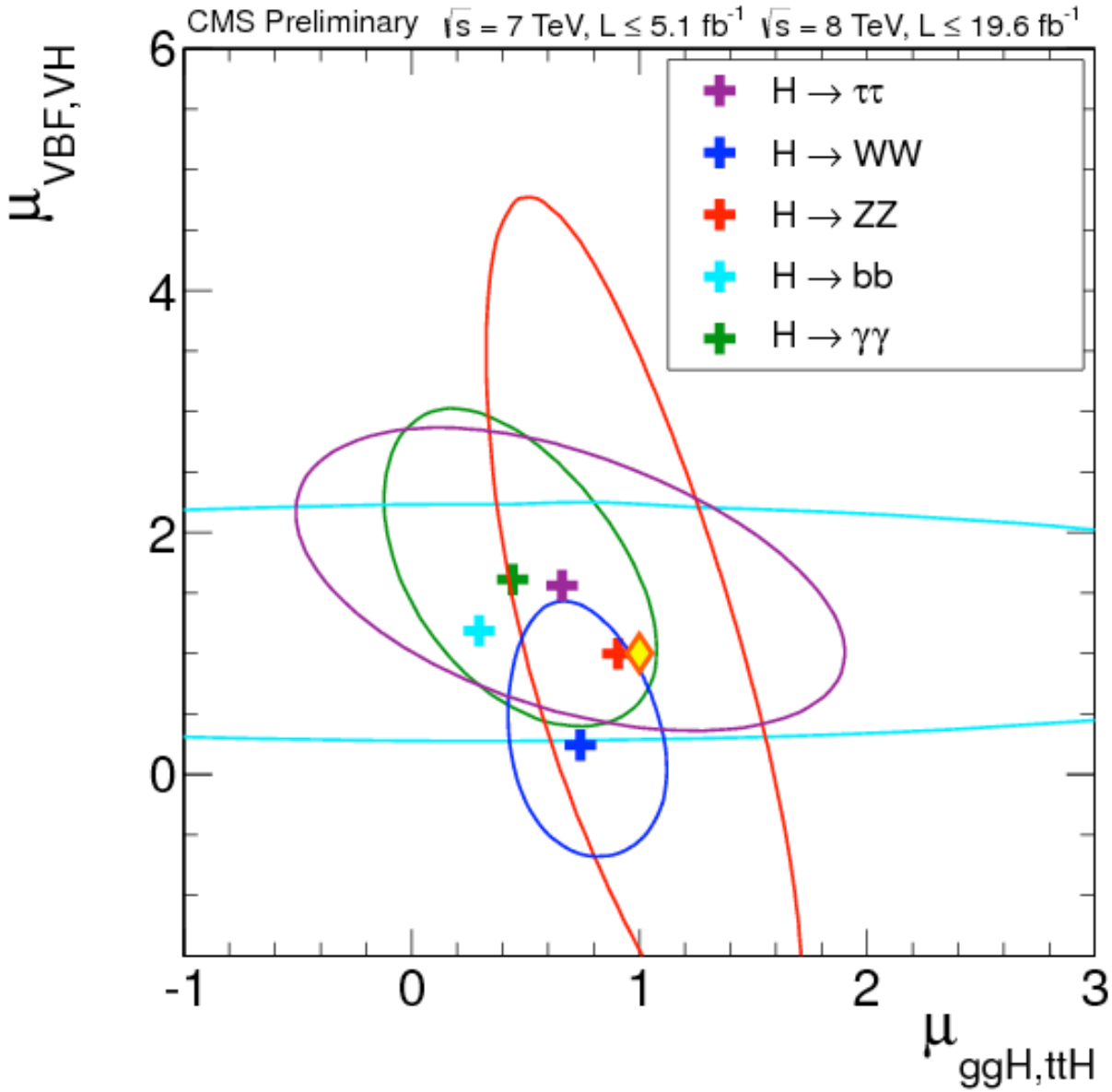


- M_H = 125.7 ± 0.4(stat.) ± 0.4(syst.) GeV

NEW

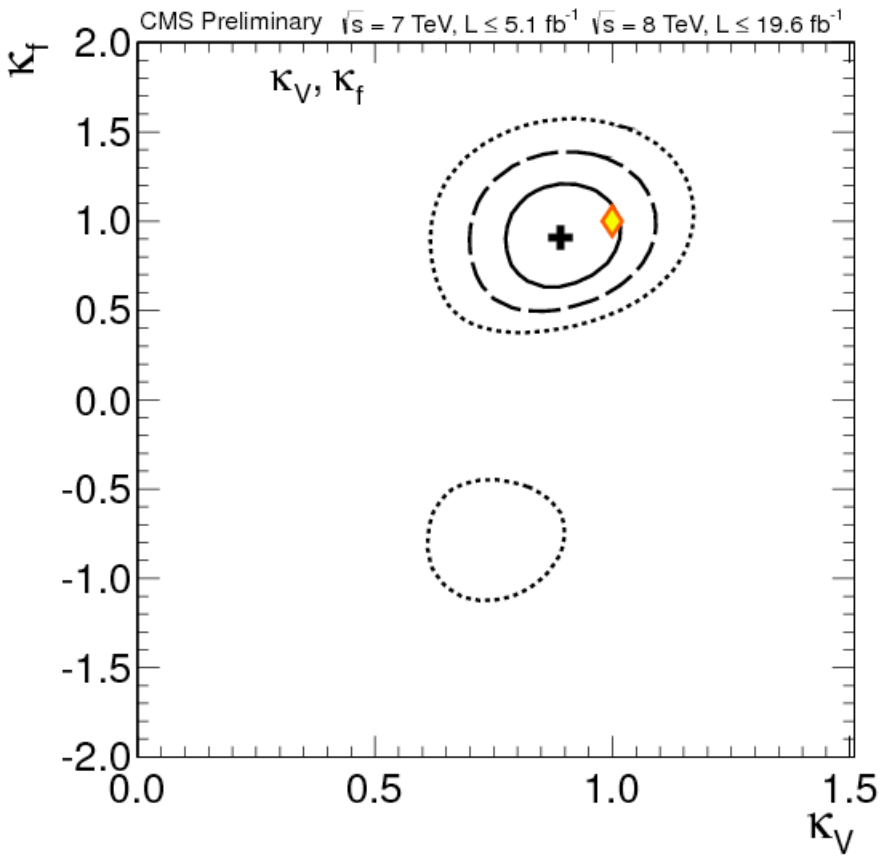
- Γ_H < 6.9 (expected 5.9) GeV at 95% CL (From H->γγ)

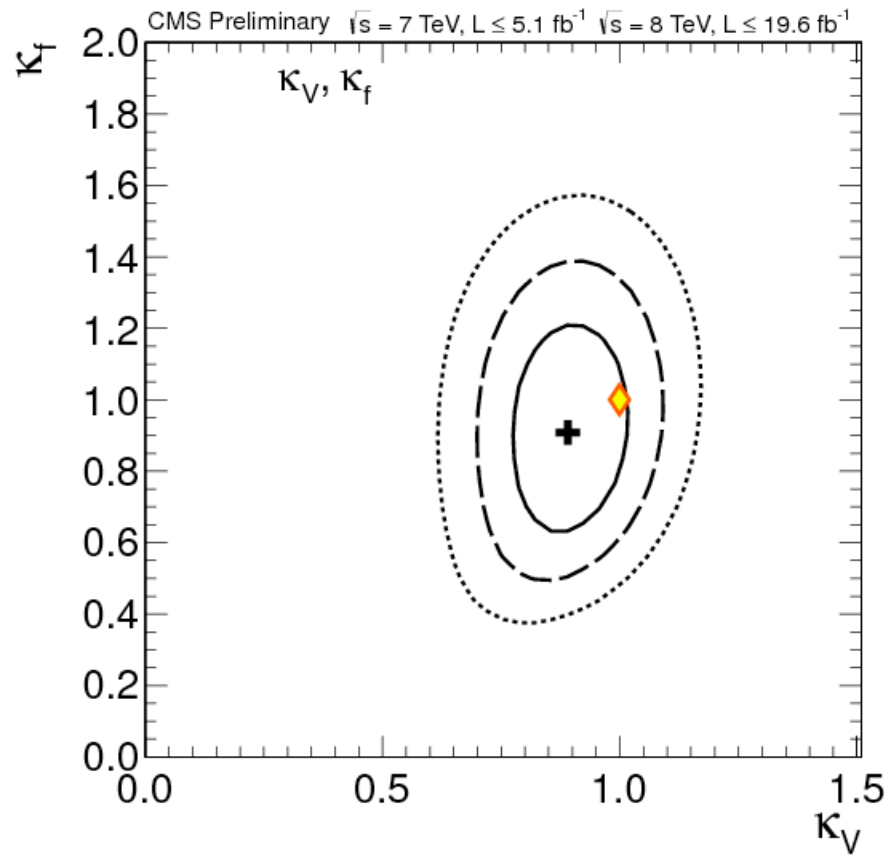
$\mu_{ggH,ttH}$ vs $\mu_{VBF,VH}$



CMS: κ_V, κ_f contours

- Vector and fermion couplings are scaled by two scale factors , κ_V and κ_F
- Agree with SM at ~1 σ





CMS: κ_V, κ_f contours

- Vector and fermion couplings are scaled by two scale factors , κ_V and κ_F
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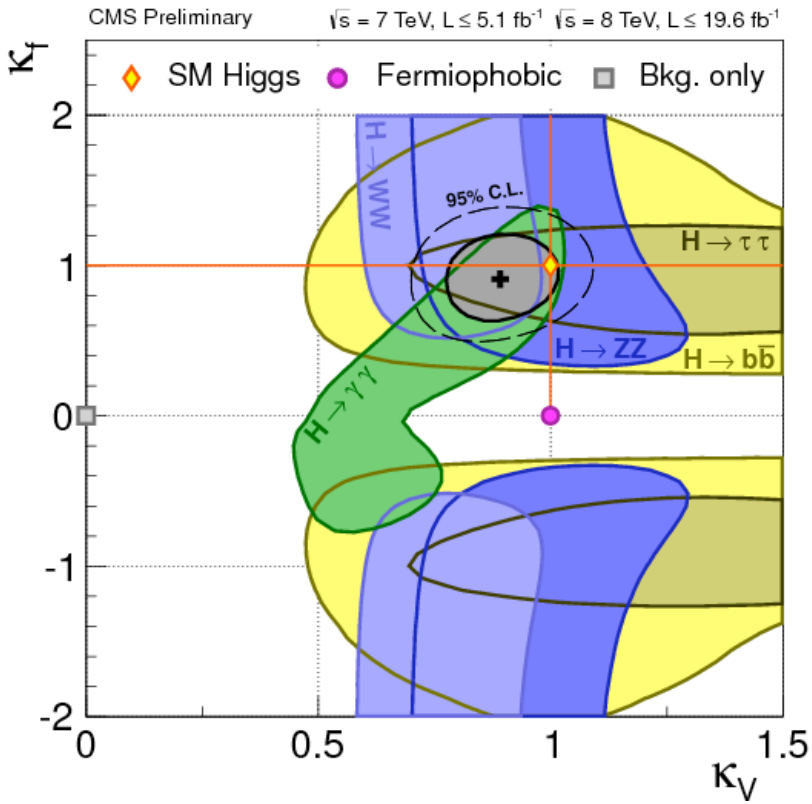
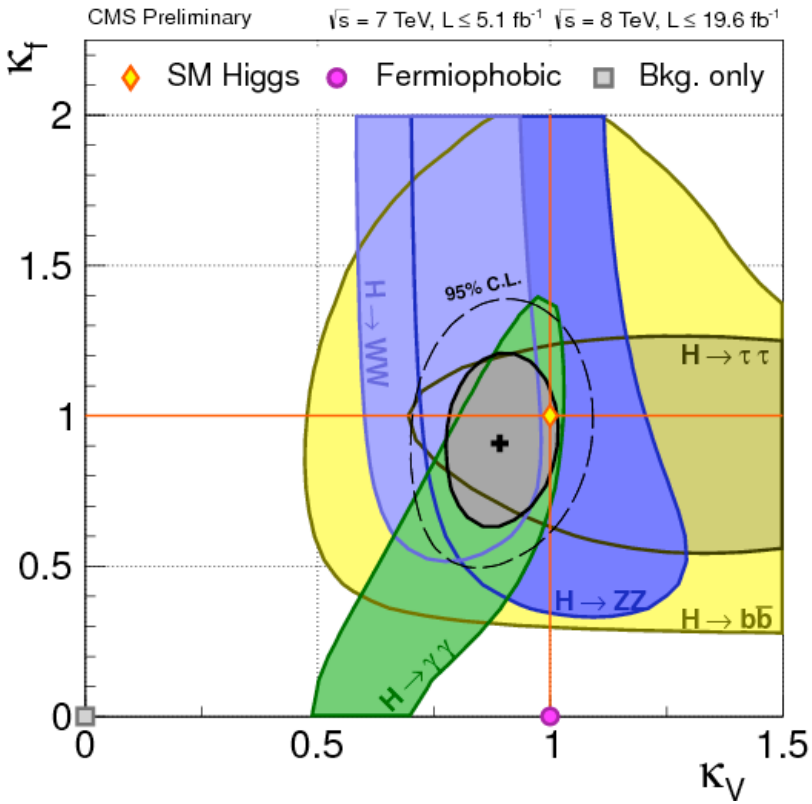
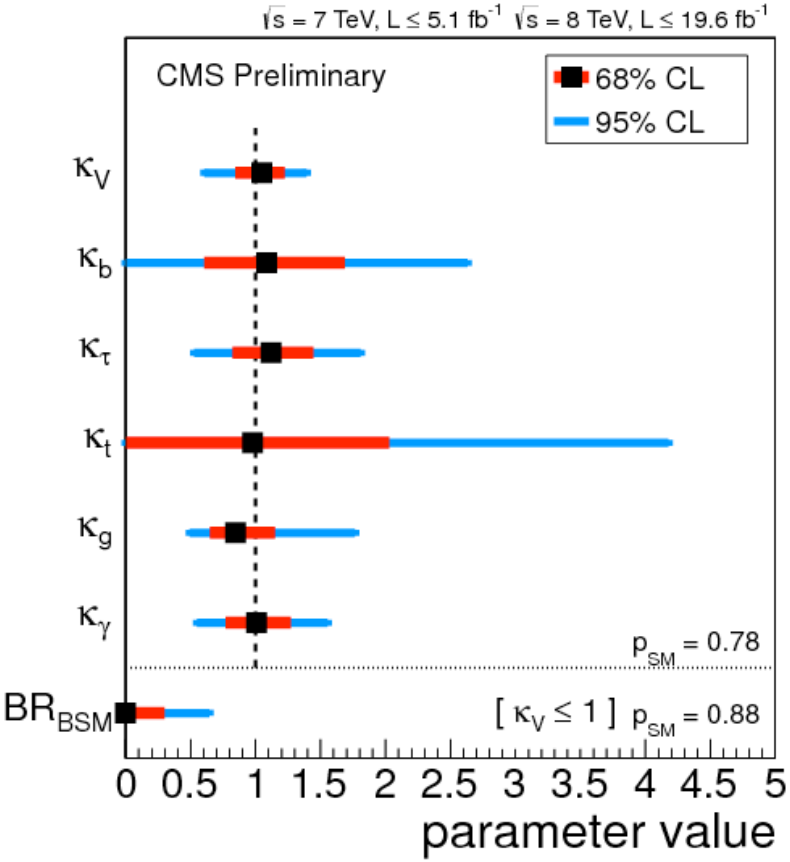
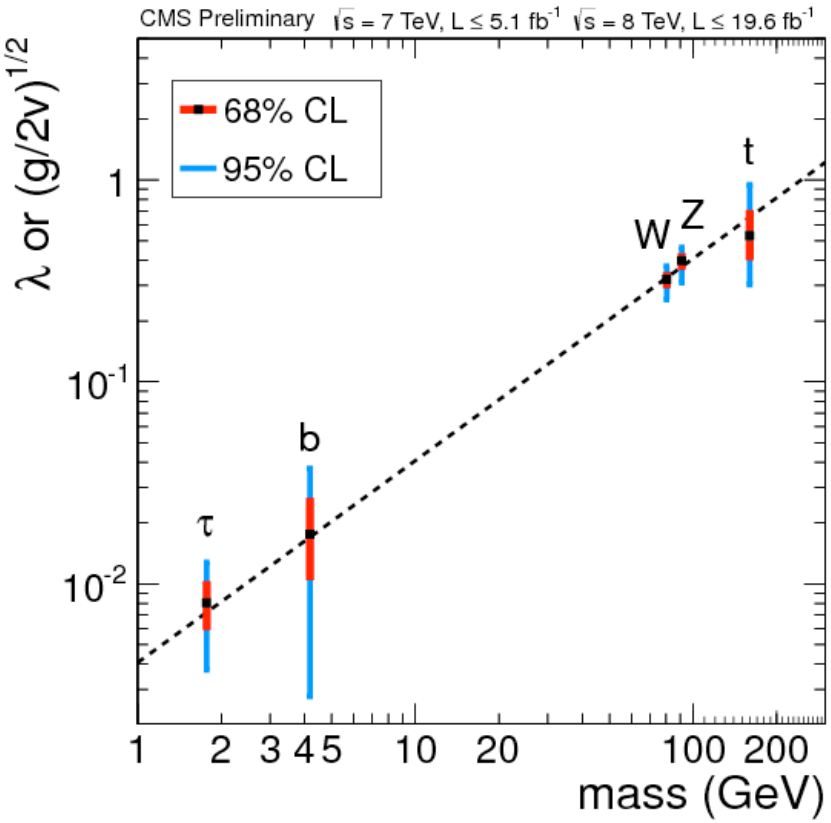




Coupling measurements

six-parameter model including effective loop couplings

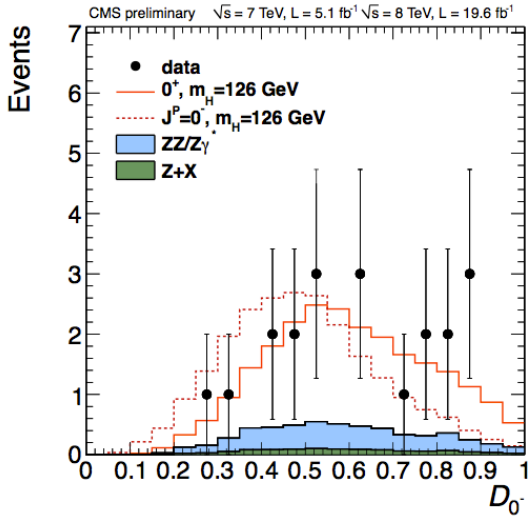


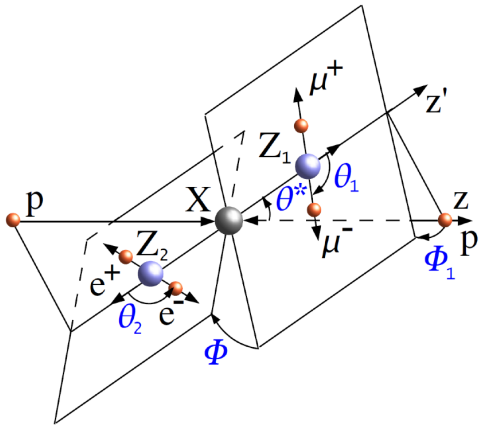


- $BR_{BSM} < 0.64$ at 95% C.L. (with $\kappa_V \leq 1$)

Spin-parity analysis

- Spin and parity can be probed using angular distributions
- Best channel is H->ZZ where all angles are measured
  - Using discriminators similar to K_D we can distinguish between scalar and pseudo-scalar and different spin hypotheses





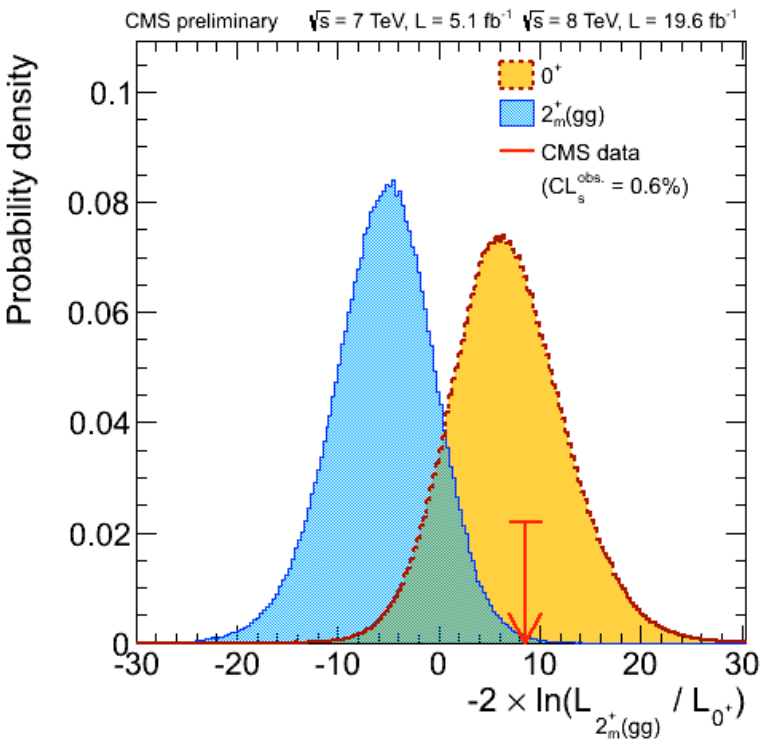
From ZZ using the full dataset

J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0^+_h	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2^+_{mgg}	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2^+_{mq\bar{q}}$	$q\bar{q} \to X$	minimal couplings	1.7σ (1.9σ)	1.8σ	4.0σ	<0.1%
1^-	$q\bar{q} \to X$	exotic vector	2.8σ (3.1σ)	1.4σ	$>4.0\sigma$	<0.1%
1^+	$q\bar{q} \to X$	exotic pseudovector	2.3σ (2.6σ)	1.7σ	$>4.0\sigma$	<0.1%

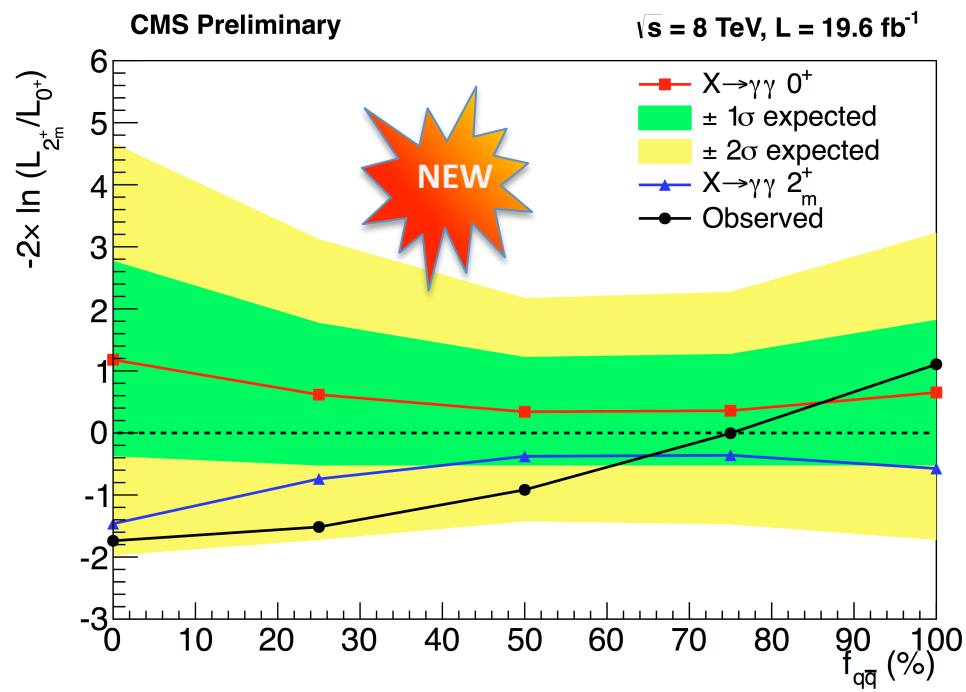
Spin 2 analysis

- Not a model independent analysis but hypothesis testing
- Consider graviton-like hypothesis 2^+_m
- Production can be gg fusion or qq annihilation

Combination of WW and ZZ
Dominated by ZZ
Excludes 2^+_m 100% gg-fusion hypothesis at 99.4 % CL



Hgg Spin analysis
Sensitivity still rather low
No 95% CL exclusions from this channel



CMS PAS HIG-13-016

BSM Higgs studies

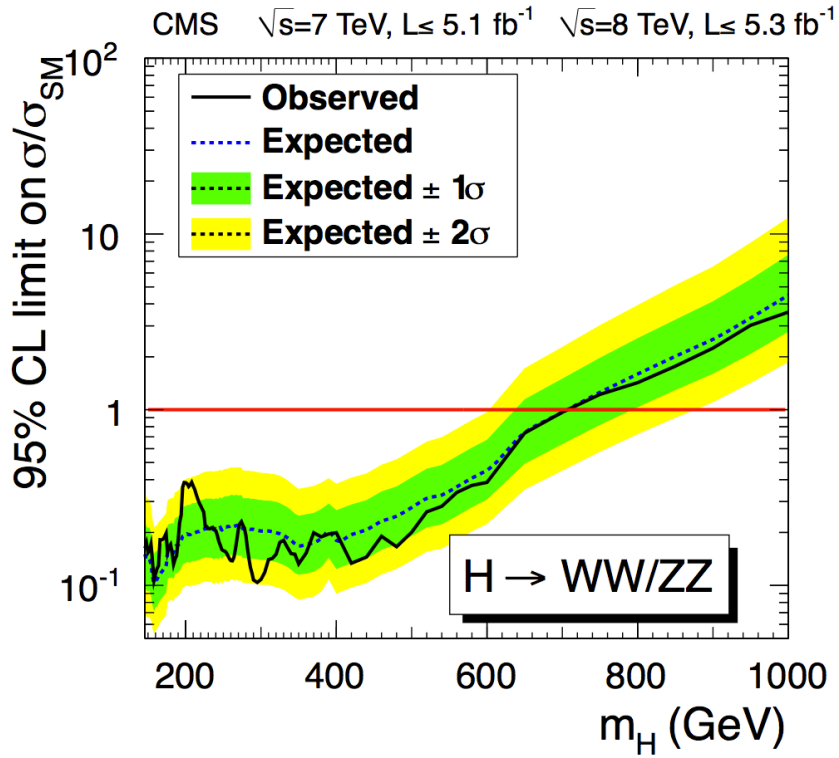
- High mass Higgs
  - BSM even if SM like, given H125 observation
  - Interpretation as additional Higgs singlet
- Modified SM
  - Fermiophobic Higgs
- MSSM/2HDM
  - neutral Higgs bosons - decays into μμ, ττ and bb
  - charged Higgs bosons – decays into τν
  - double Higgs in H->γγ

High mass searches

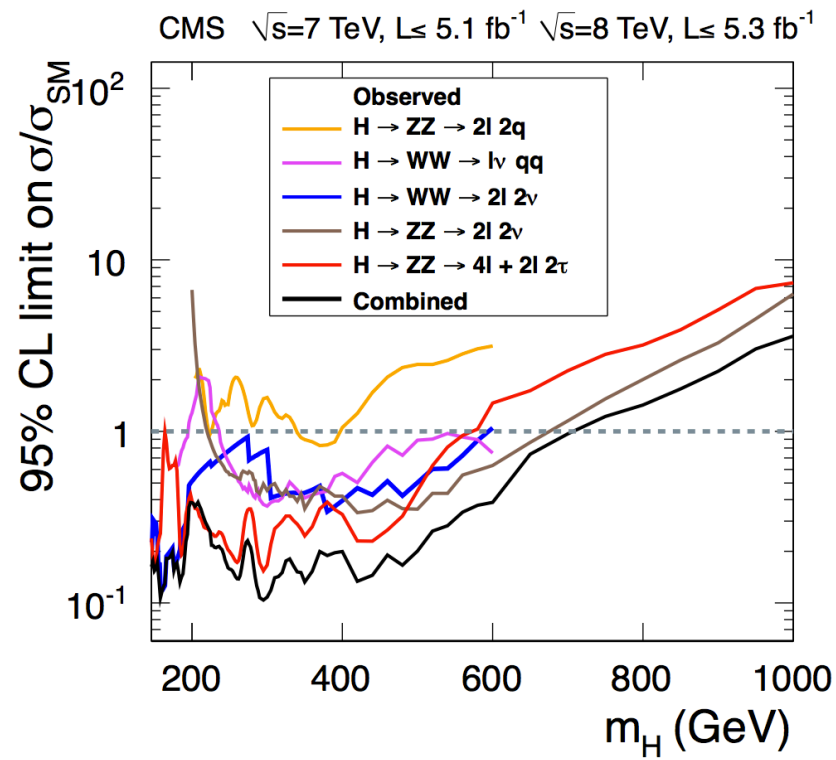
- High mass: WW and ZZ decays
  - add WW→lνqq, ZZ→2l2ν, ZZ→2l2q, ...

EPJC 73 (2013) 2469.

Expected and observed combined



Observed in different channels

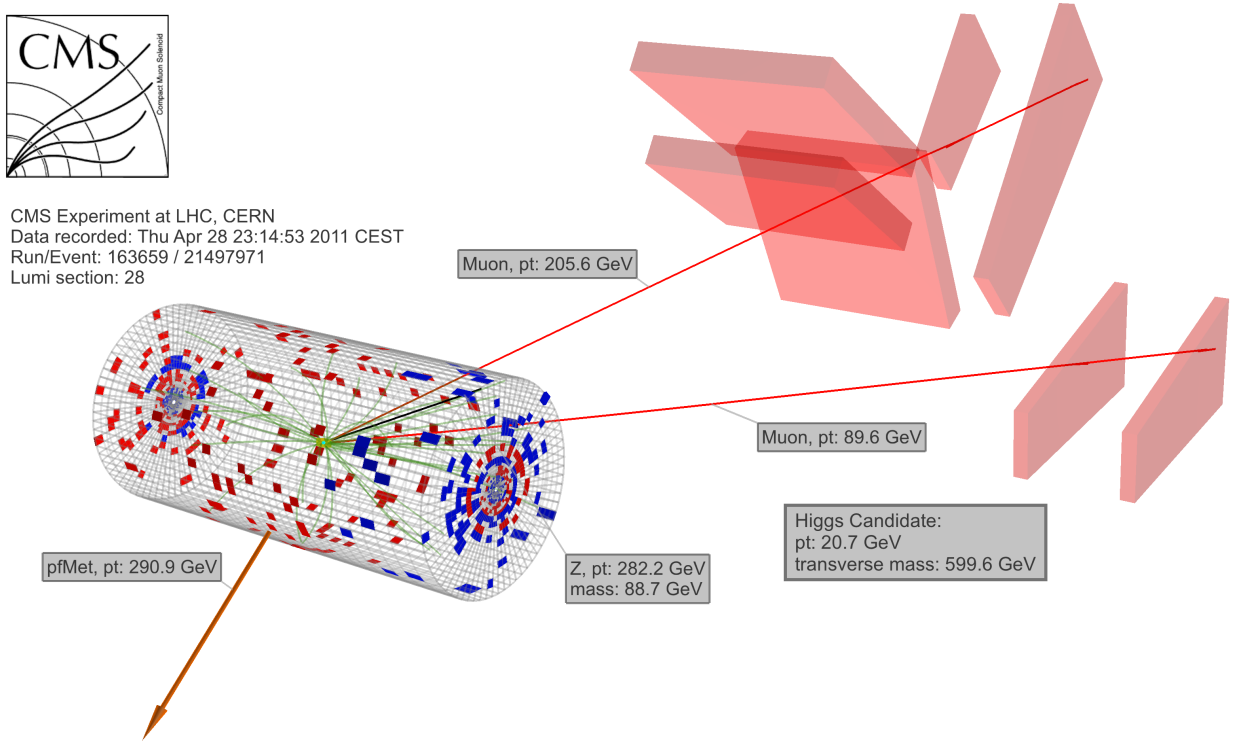


- Published results
  - SM Higgs boson excluded at 95% CL in the mass range 127 – 710 GeV

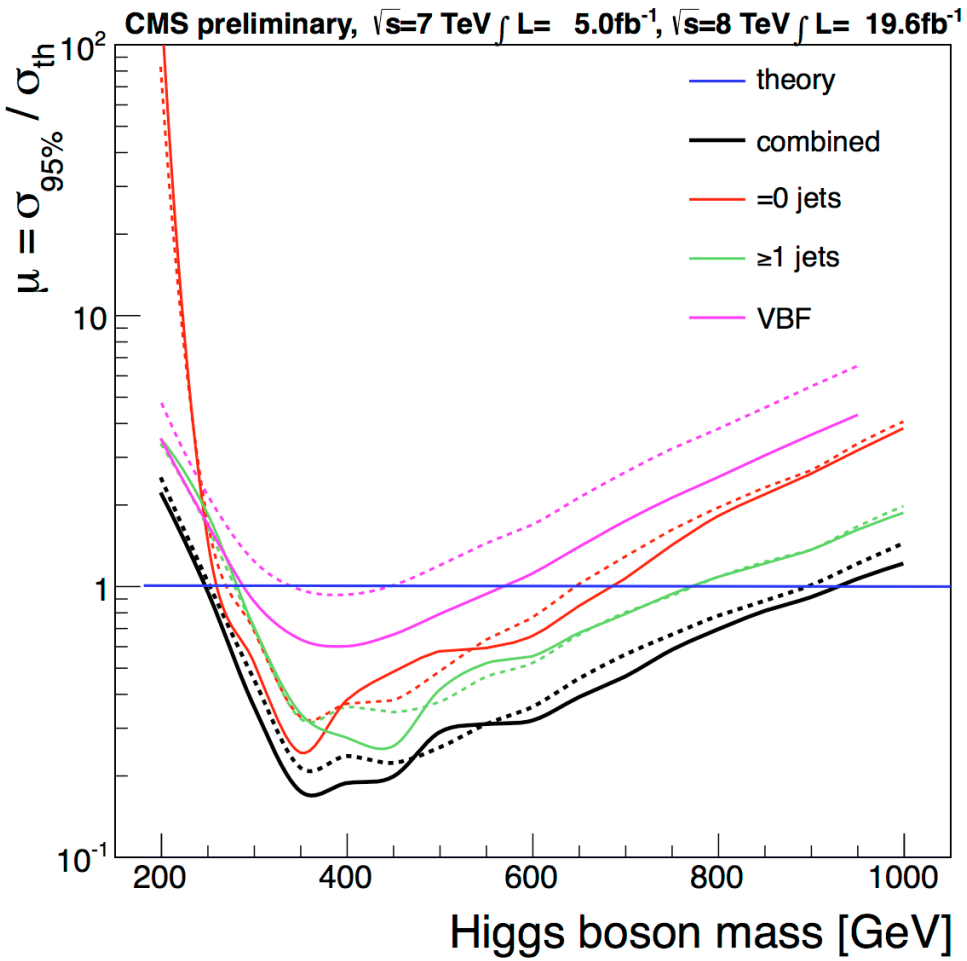
High mass: H→ZZ→llvv channel

- Most sensitive channel for high mass search
  - BR 6 times larger than ZZ→4l
- **Missing neutrinos implies mass resolution 7%**
- Only accessible for high mass (M_H > 200 GeV):
  - the two Z bosons are boosted
  - large MET due to invisible decay
- Main backgrounds
  - ZZ (irreducible)
  - Z+jets, tt, WZ

H->ZZ->llvv candidate



H→ZZ→llνν results

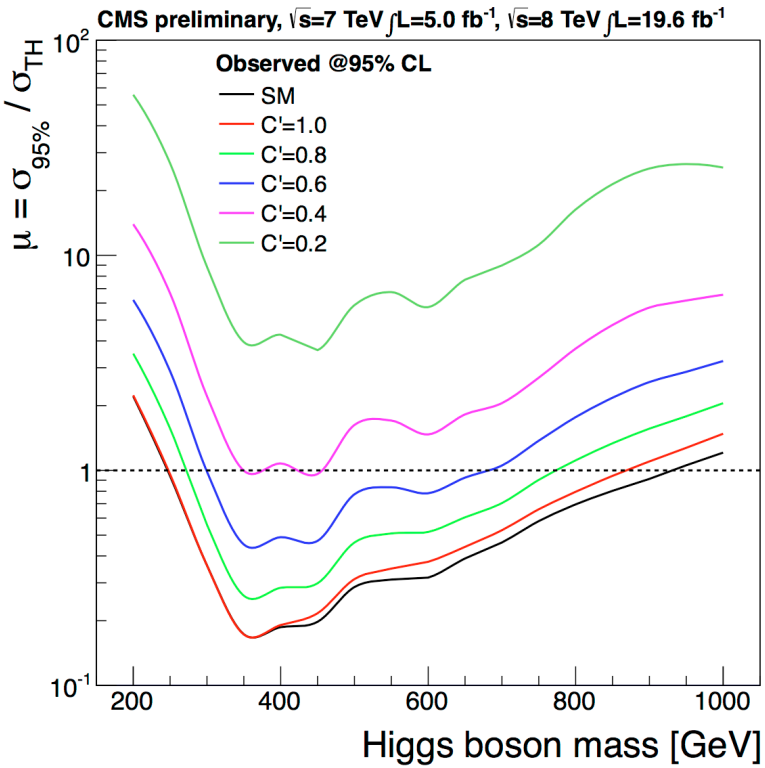


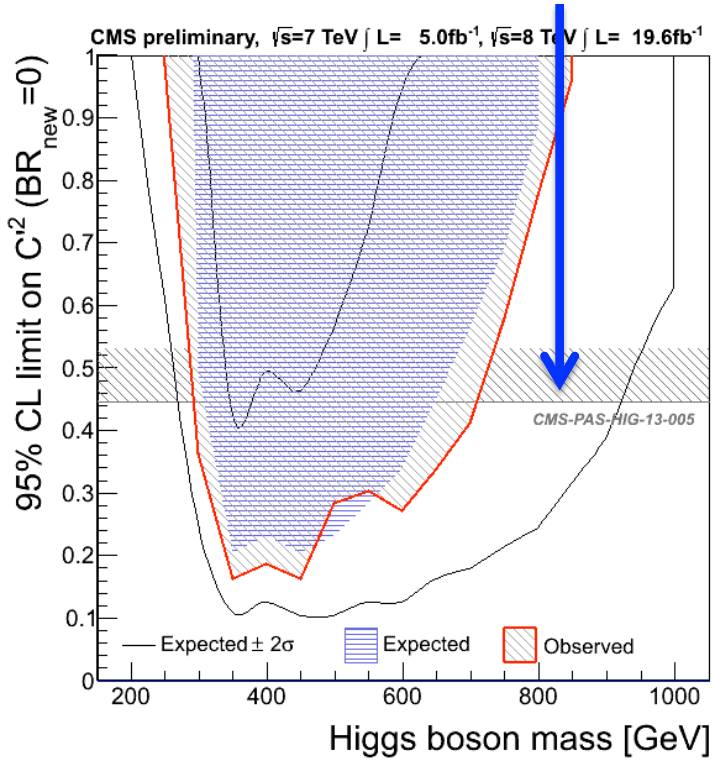
- No signal observed
- Excluded at 95% CL mass range 248 – 930 GeV

Interpretation as additional EW singlet

- H(125) and h' have couplings scaled by C and C'
- $C^2 + C'^2 = 1$
- $\mu' = C'^2 x(1-BR_{new})$
- Width for h' is $\Gamma' = C'^2\Gamma/(1-BR_{new})$
- Assuming $BR_{new}=0$ we set limits on μ' and C'

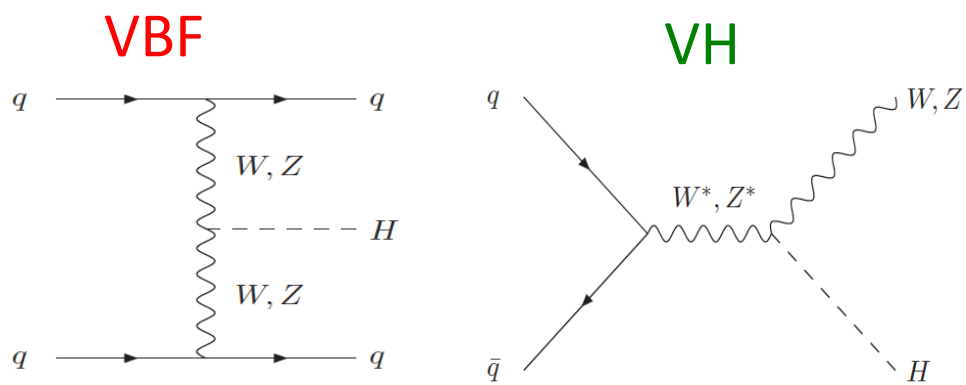
From μ(H125) = 0.80±0.14
$C'^2 < 0.446$ at 95% CL

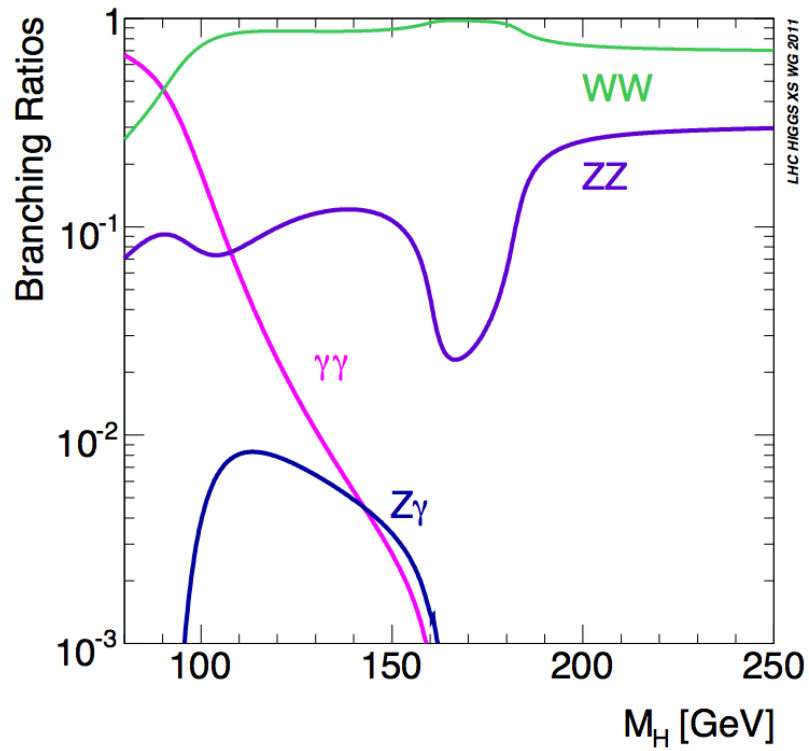




Search for a Fermiophobic Higgs boson

- Fermiophobic (FP) Higgs boson only couples to vector bosons
- gg-fusion and tt-fusion not allowed at tree level
- No bb and ττ decays. WW, ZZ and γγ BR enhanced at low mass
- Exclusive VBF searches and VH searches, same as in SM analysis

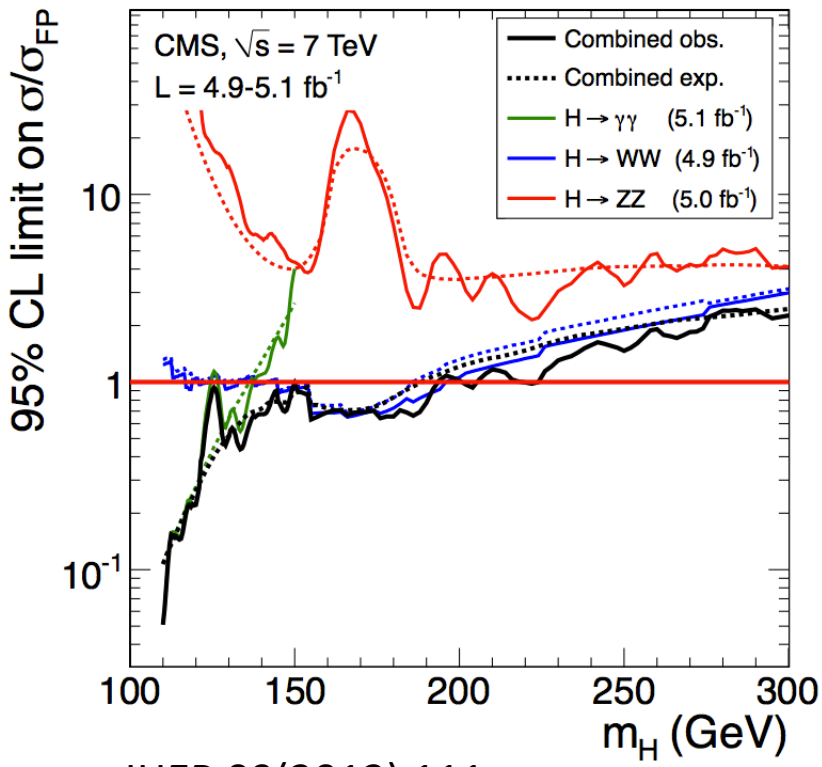




FP results

- Excluded in a pure FP model
  - At 95% CL 110-194 GeV from combination of 2011 data
  - At 95% CL 110-147 GeV from γγ alone

2011 7 TeV data: combined channels



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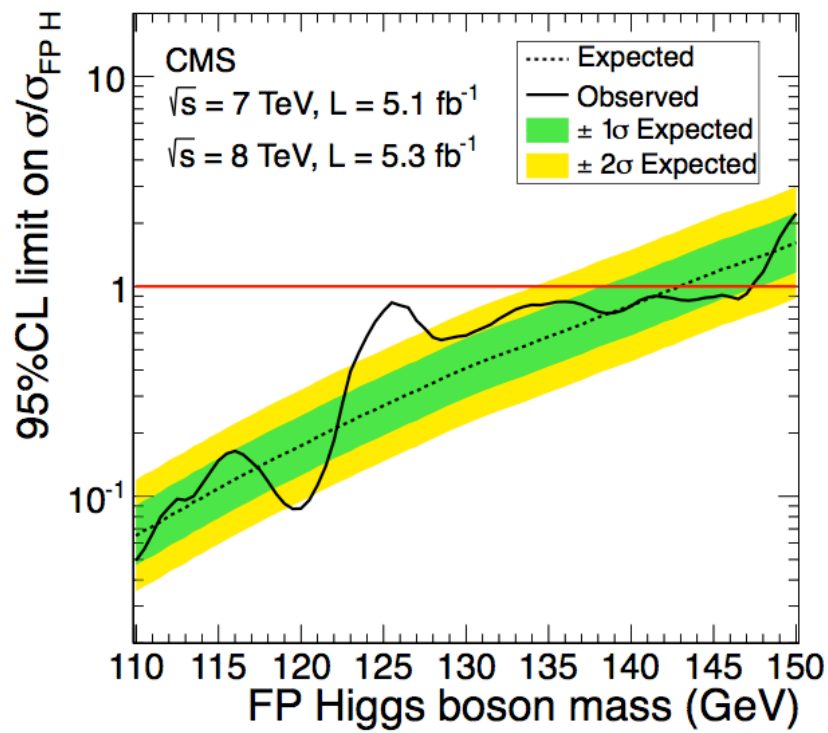
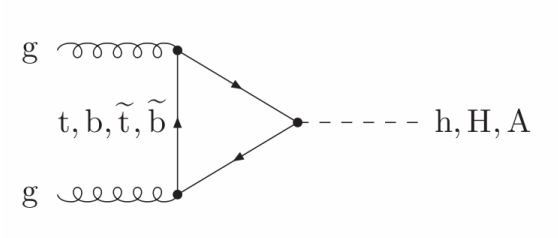
7+8 TeV data: γγ channel

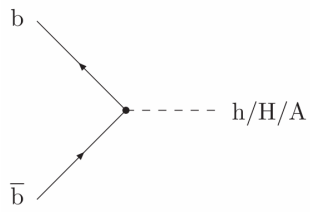


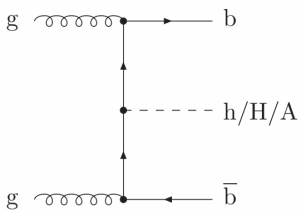
arXiv:1302.1764
accepted by PLB

MSSM Higgs bosons: Φ (h,H,A), Φ→ττ,bb,μμ

- In MSSM Φ can be produced by gg fusion or bb annihilation

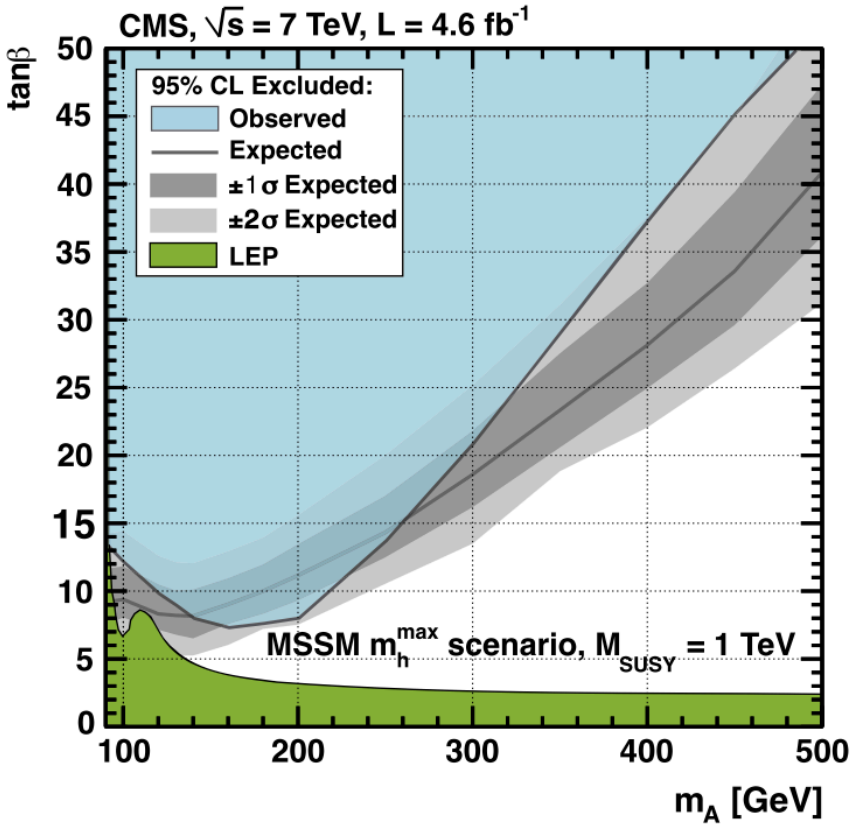






Often at least one b jet produced in the central detector

- **Φ→ττ is the most sensitive**
- **No significant excess observed**

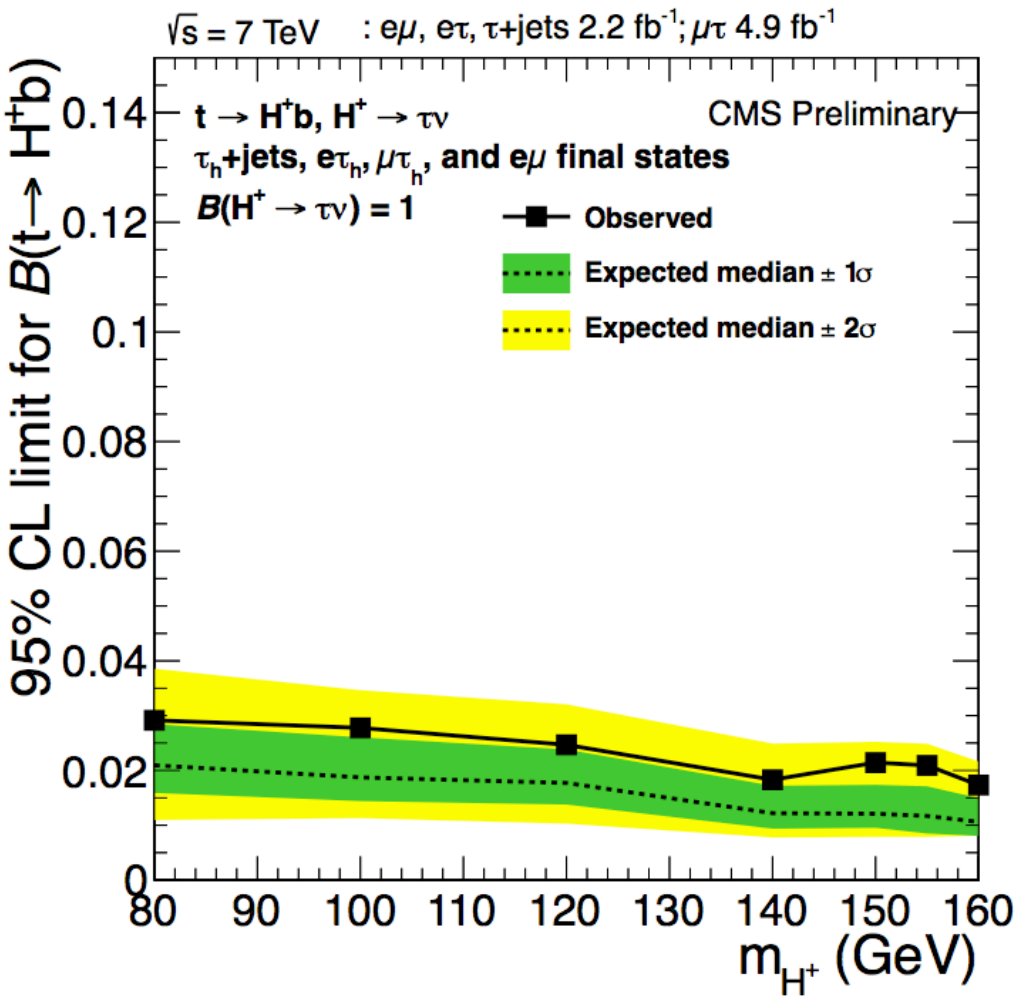


Excluded region at large tanβ

Phys. Lett. B 713 (2012) 68

$H^{\pm} \rightarrow \tau\nu$

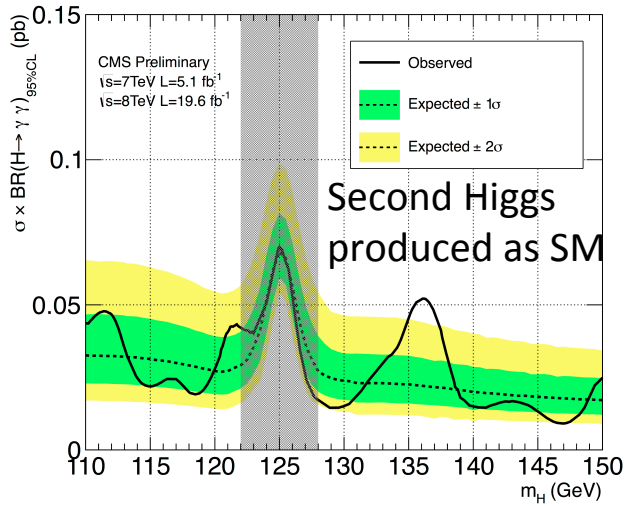
- Charged Higgs are searched for in top decays for M_{H^+} in the range 80-160 GeV ($M_{H^+} < M_{top}$)
  - $t\bar{t} \rightarrow H^{\pm}W^{\mp}b\bar{b}$, $t\bar{t} \rightarrow H^{\pm}H^{\mp}b\bar{b}$
- Search for $H^{\pm} \rightarrow \tau\nu$ (favoured for large tanβ)
- No signal observed
- 95% CL limit on $BR(t \rightarrow bH^+)$ of 2-4% assuming $BR(H^+ \rightarrow \tau\nu) = 1$

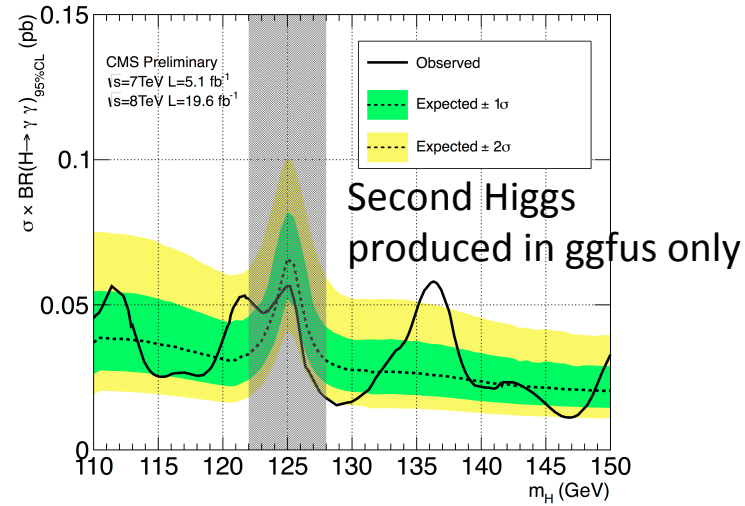


H→γγ - double Higgs

- H125 used as additional BG

CMS PAS HIG-13-016

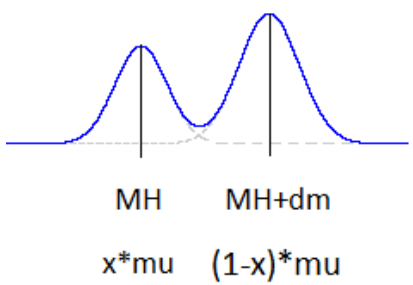


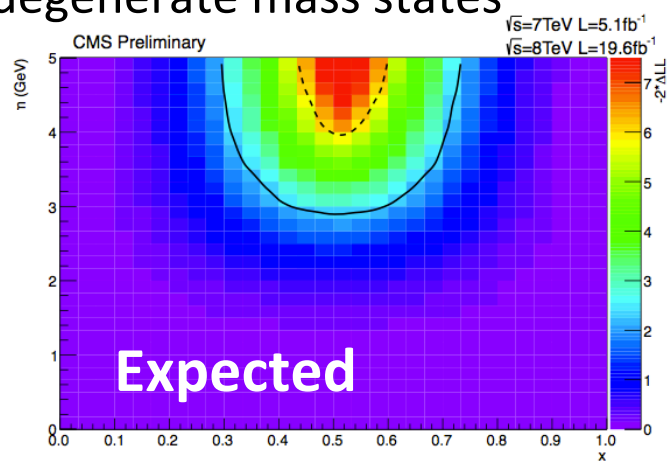


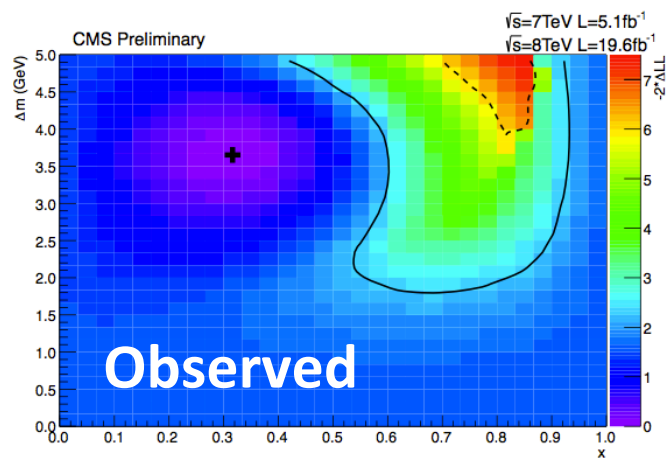
$M_{H'}$=136.5
Local significance 2.9 σ
Global significance <2σ

NEW

- Two nearly degenerate mass states



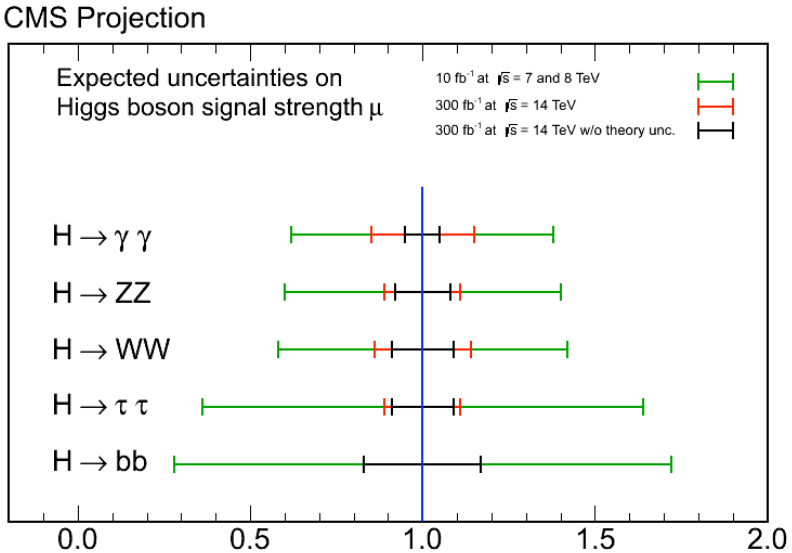




Allows to exclude parameters in the 2HDM when two Higgs boson interpreted as h,H or h,A

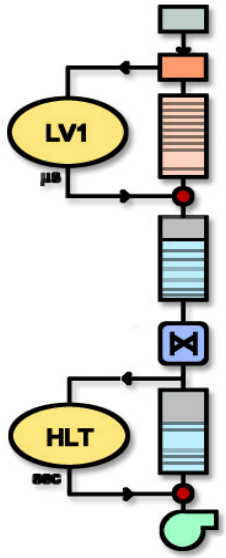
Summary and outlook

- LHC performed extremely well during the last 3 years and the full data set has been analyzed
- After the discovery of the H125 Higgs boson we started to measure its properties
  - Branching ratios and couplings are found to be in general agreement with the SM
  - Angular distributions are consistent with the J^P 0^+ hypothesis
- No evidence of BSM Higgs bosons, improved limits are obtained in different scenarios
- Entered two years of LHC shutdown to prepare the higher energy and resume data taking in 2015 at 13/14 TeV:
  - Expect with 300 fb^{-1} a precision of O(10%) on couplings and BRs



Backup

Level1 and High Level Trigger in CMS



40 MHz

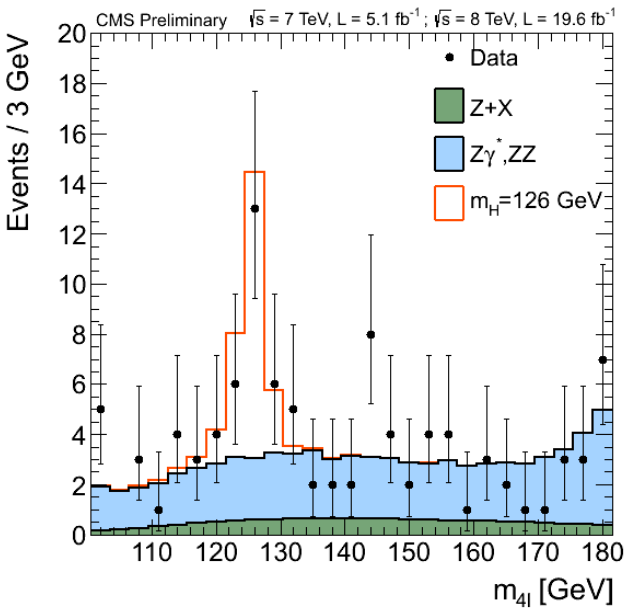
100 KHz

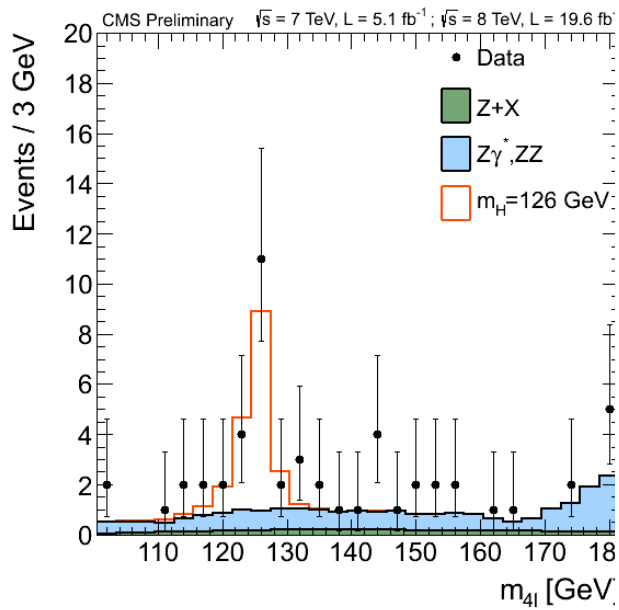
~300 Hz

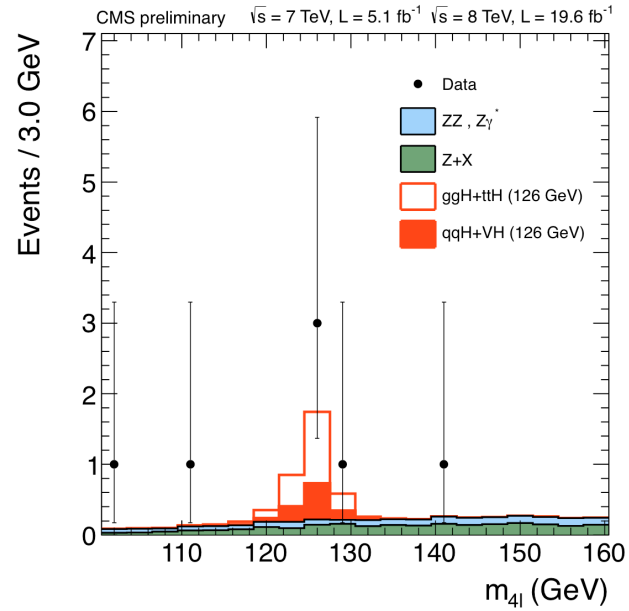
- 2-level trigger system
- Design input: 40 MHz (currently 20 MHz)
- Level1 output 100 KHz
- High Level Trigger output ~300 Hz (saved for physics analysis)

- The HLT has access to the full event information and runs the offline reconstruction only optimized for speed
- ~500 HLT paths select events for all analyses
  - Single object triggers: e, γ, μ, MET, …
  - Multi object triggers: ee, γγ, μμ, e+MET, …
  - Prescaled triggers used for control samples and to measure efficiencies, including trigger efficiency

H → ZZ → 4l

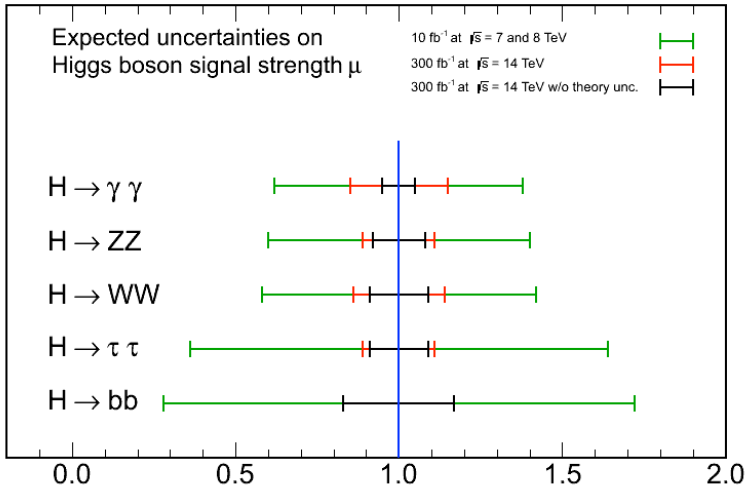

CMS Preliminary √s = 7 TeV, L = 5.1 fb-1 ; √s = 8 TeV, L = 19.6 fb-1
Data
Z+X
Zγ*,ZZ
mH=126 GeV
Events / 3 GeV
m4l [GeV]


CMS Preliminary √s = 7 TeV, L = 5.1 fb-1 ; √s = 8 TeV, L = 19.6 fb-1
Data
Z+X
Zγ*,ZZ
mH=126 GeV
Events / 3 GeV
m4l [GeV]

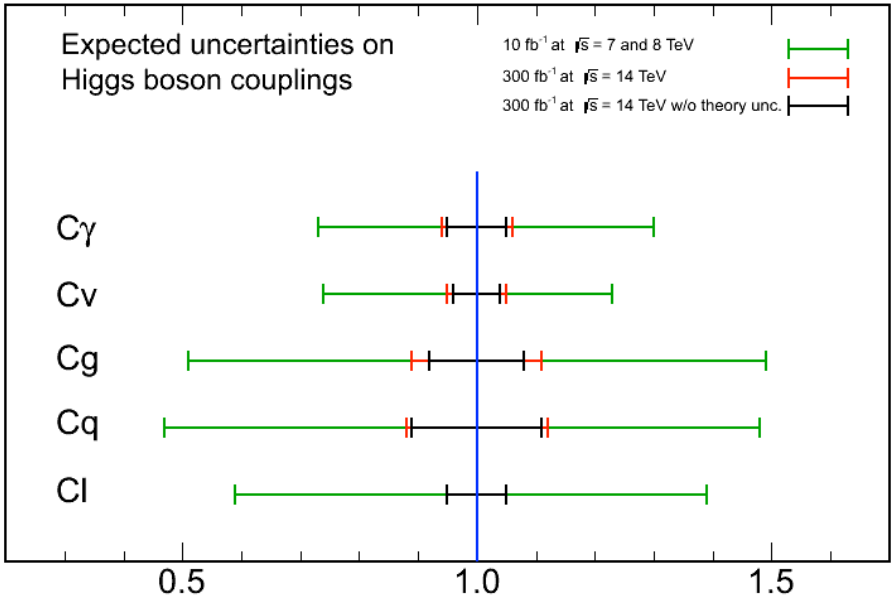

CMS preliminary √s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 19.6 fb-1
Data
ZZ , Zγ*
Z+X
ggH+ttH (126 GeV)
qqH+VH (126 GeV)
Events / 3.0 GeV
m4l (GeV)

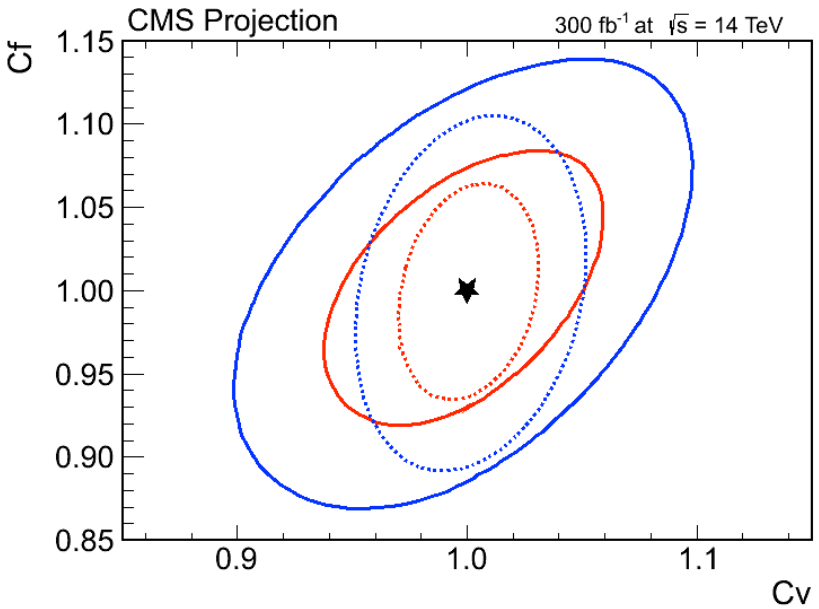
Projections at 14 TeV

CMS Projection



CMS Projection

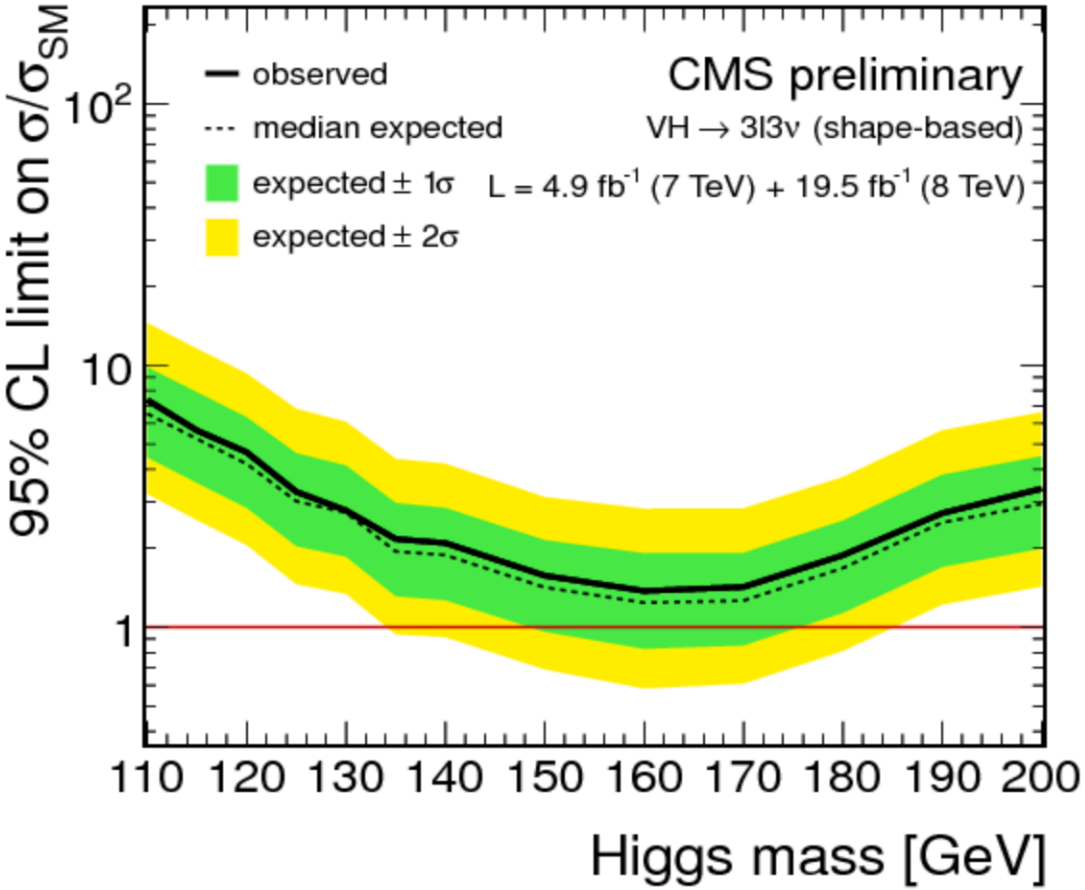




WH→WWW→3l3ν

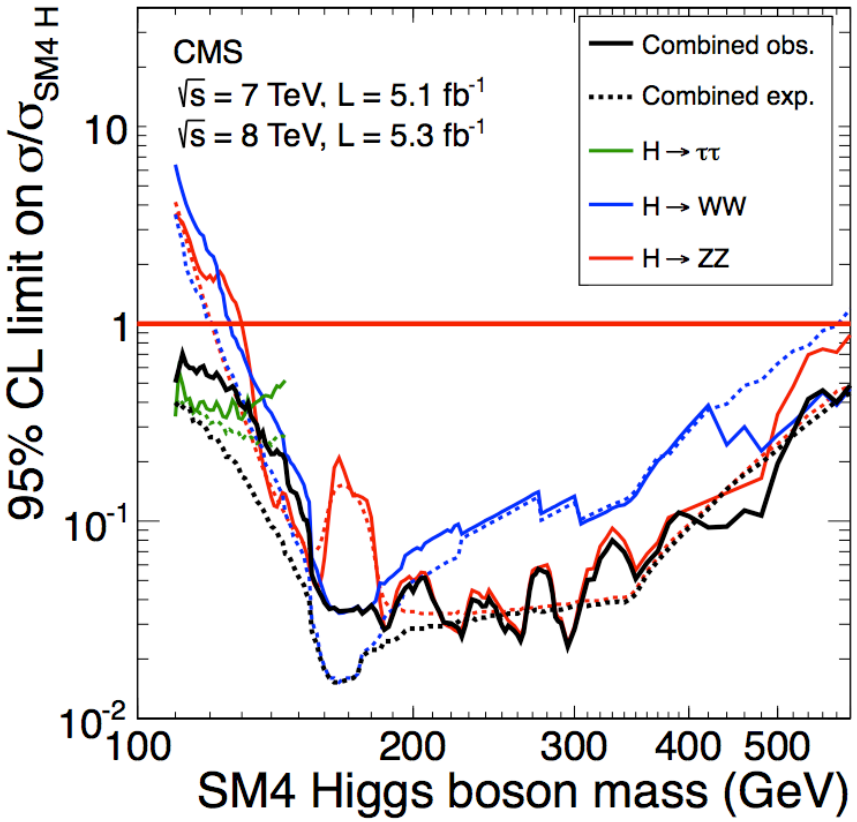
- Similar to WW analysis
- Cut and count analysis with mass independent selection
- Main backgrounds estimated from data

CMS PAS HIG-13-009



4 fermion generations model

- A 4th generation of fermions mainly increases the gg-fusion cross section
- Assume:
  - $M_{D4}=M_{L4}=600$ GeV
  - $M_{U4} - M_{D4} = [\ 1 + 1/5*\ln(M_H/115)\ ] * 50$ GeV
- Reinterpretation of SM Higgs searches
- **Excluded at 95% CL M_H in [120-600] GeV**



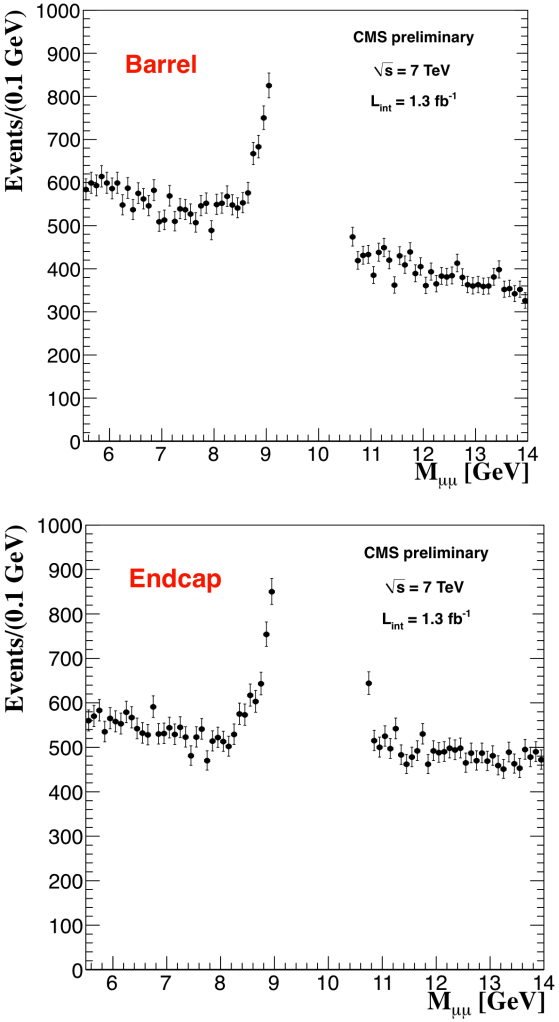
NMSSM: $a_1 \rightarrow \mu^+\mu^-$

HIG-12-004

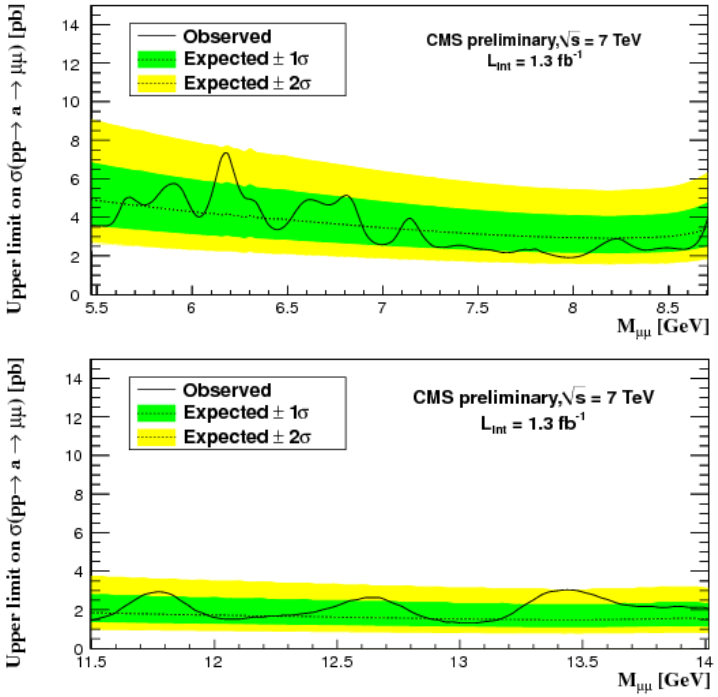
- MSSM + one additional scalar singlet
- One more scalar and one more pseudo-scalar:

  $a_1 = a_{MSSM}\cos(\theta_A) + a_S \sin(\theta_A)$ (could be at low mass)
- Search in the dimuon mass spectrum around the Υ

Dimuon mass spectrum

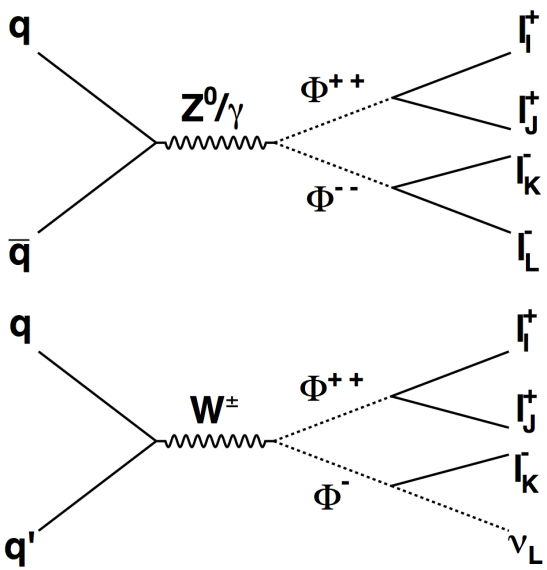
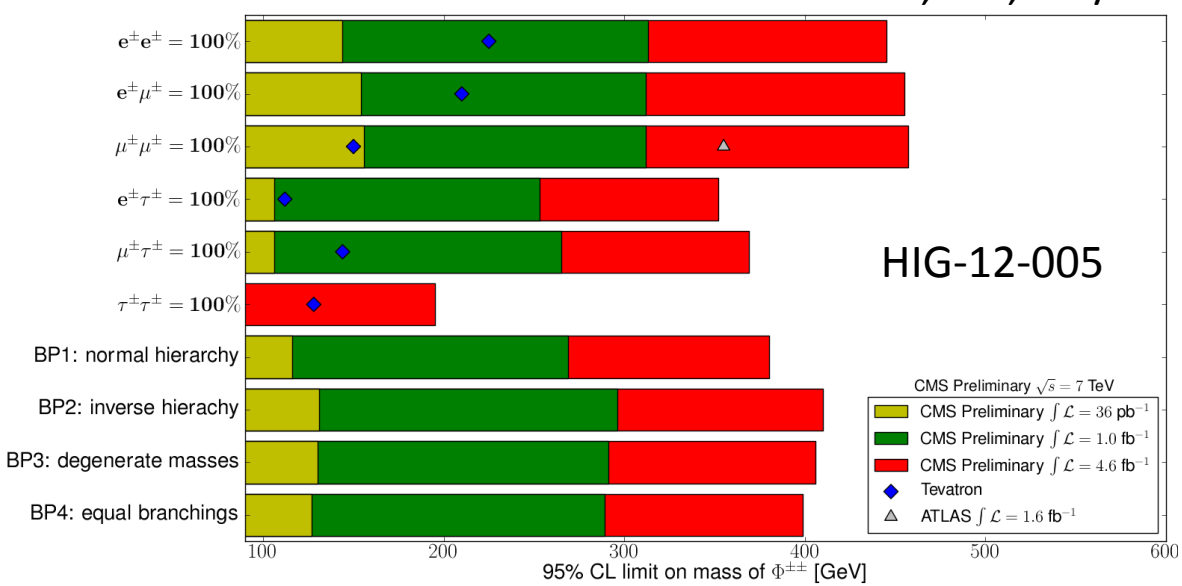


σ x BR upper limits (pb)



Doubly charged Higgs

- Minimal Type II See-Saw Models with an additional triplet predict additional Higgs particles: Φ±±, Φ±, Φ0
- Possible explanation for neutrino masses
- Search for pair production or associated production with Φ++Φ-
- Φ±±, Φ± are assumed to be degenerate in mass
- Signature is 3 or 4 charged leptons
  - Search for resonant same sign leptons from Φ±± in all possible flavours



7 TeV CMS 95% lower limit : 0.036, 1.0, 4.6/fb